Improving Economics of Solar Power Through Resource Analysis, Forecasting, and Dynamic System Modeling

Jan Kleissl
Professor, Mechanical & Environmental Engineering,
UC San Diego
Center for Renewable Resources and Integration
http://solar.ucsd.edu, jkleissl@ucsd.edu

Utility: Bill Torre, Dallas Cormier, Steven Garrett (SDG&E)
CAISO: Jim Blatchford Subcontractor: Jens Schoene (Enernex)

Improved Modeling Tools Development at UCSD for High Penetration of Solar PV

The goal of the project is to accelerate the placement of higher levels of Photovoltaics into electric distribution circuits.

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Solar Resource Assessment and Forecasting

Overview

- PV Impacts on Distribution Feeders (Enernex)
  → Effect of input data to feeder studies.
- Solar Resource Models
  → More accurate performance prediction.
- PV Performance and Soiling Models
  → O&M impacts.
- PV Variability Models
  → Modeling of aggregate PV variability.
- Aggregate Ramp Rate Analysis
  → Real PV Impacts.

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IMPROVING ECONOMICS OF SOLAR POWER THROUGH ANALYSIS, FORECASTING, AND DYNAMIC SYSTEM MODELING

May 21, 2013

Itron CSI RD&D Program Manager

GO solar CALIFORNIA

PUBLIC UTILITIES COMMISSION EUREKA STATE OF CALIFORNIA

Outline

- Motivation
- Building the System
- Disaggregating Load & Generation
- Simulation Description & Results
- Selected Conclusions (Detailed Conclusions Attached)

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Motivation

Hypothesis: Applying conventional distribution system modeling techniques and tools for high PV penetration scenarios leads to inaccurate results and, potentially, to misleading conclusions regarding the economic consequences.

Objective: Investigate the system impact of high PV penetration in simulations more realistically by

- employing a highly detailed feeder model,
- disaggegating PV generation, and
- disaggregating load consumption.

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Building the system

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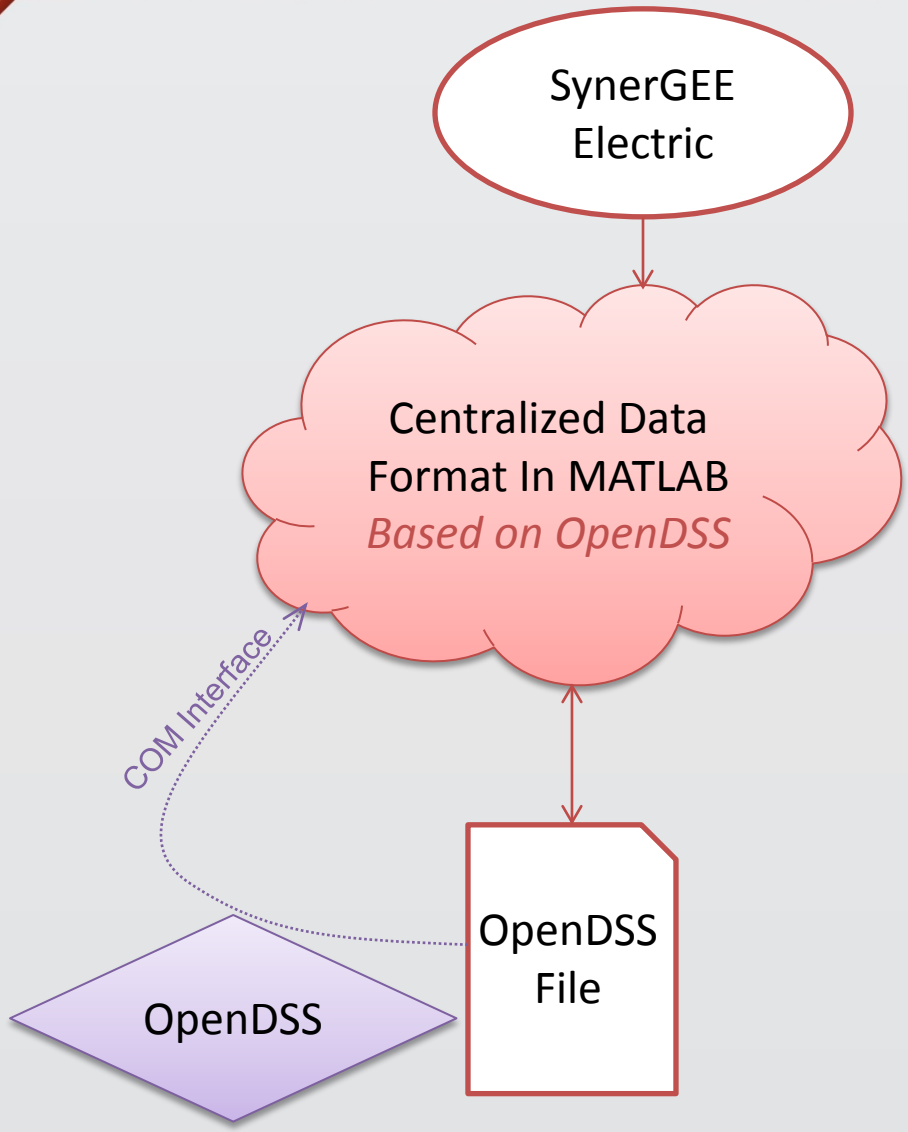
System Conversion



Feeder Parameters		Values
General	Buses	2463
	Nodes	6125
	Devices	6831
Conductors	Length of three-phase lines	312 kft / 95.1 km
	Length of two-phase lines	253 kft/ 77.1 km
	Length of single-phase lines	18.5 kft/ 5.6 km
Substation	Voltage level	12 kV_{RMS} (LL)
	Rating	28 MVA
Loads	Total active power	12.023 MW
	Number of three-phase loads	223
	Number of single-phase loads	1510
PV	Number of PV generators	45
	Total rating	2.295 MW
Transformers	Number of transformers	1 (substation)
	Number of voltage regulators	6
Capacitor Banks	Total number of capacitor banks	4
	Rating	4.430 MVAr

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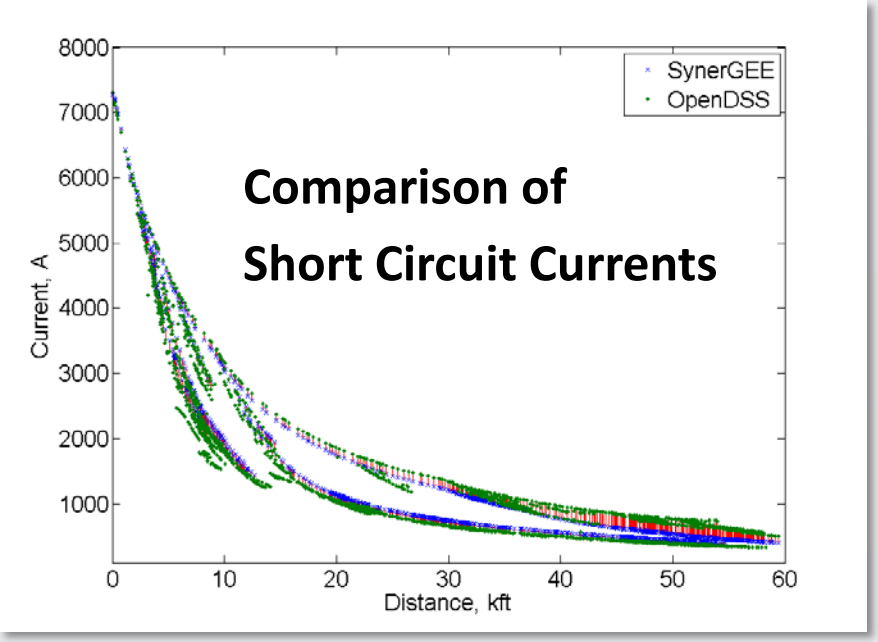
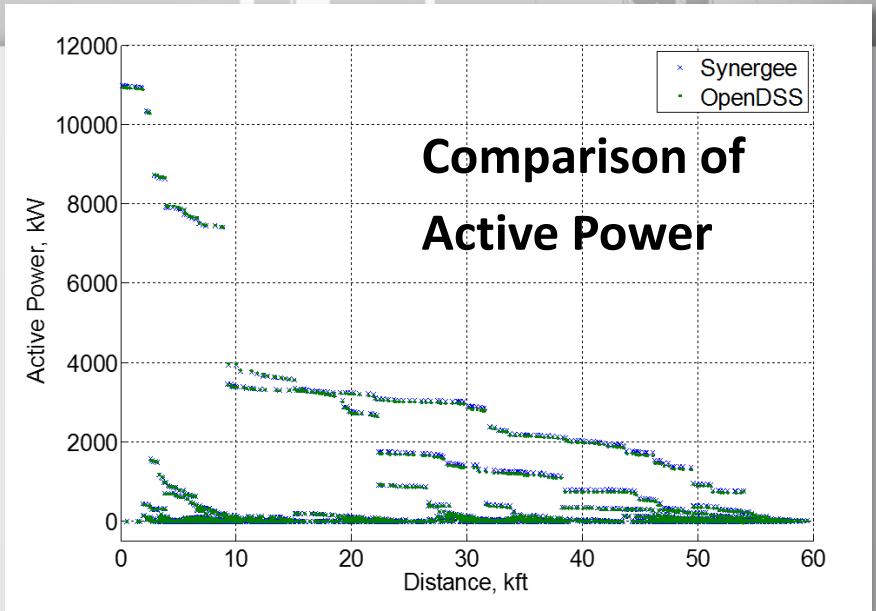
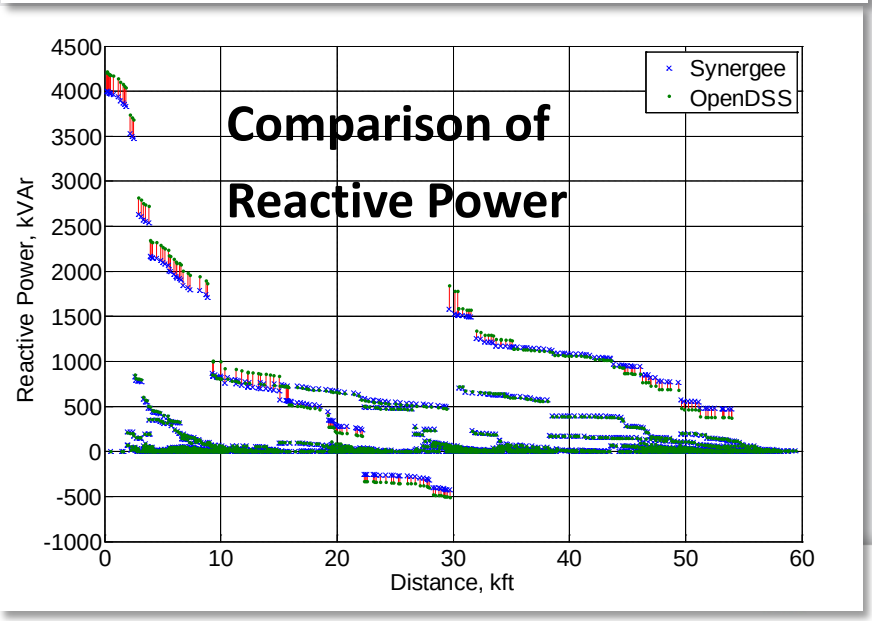
Benchmarking







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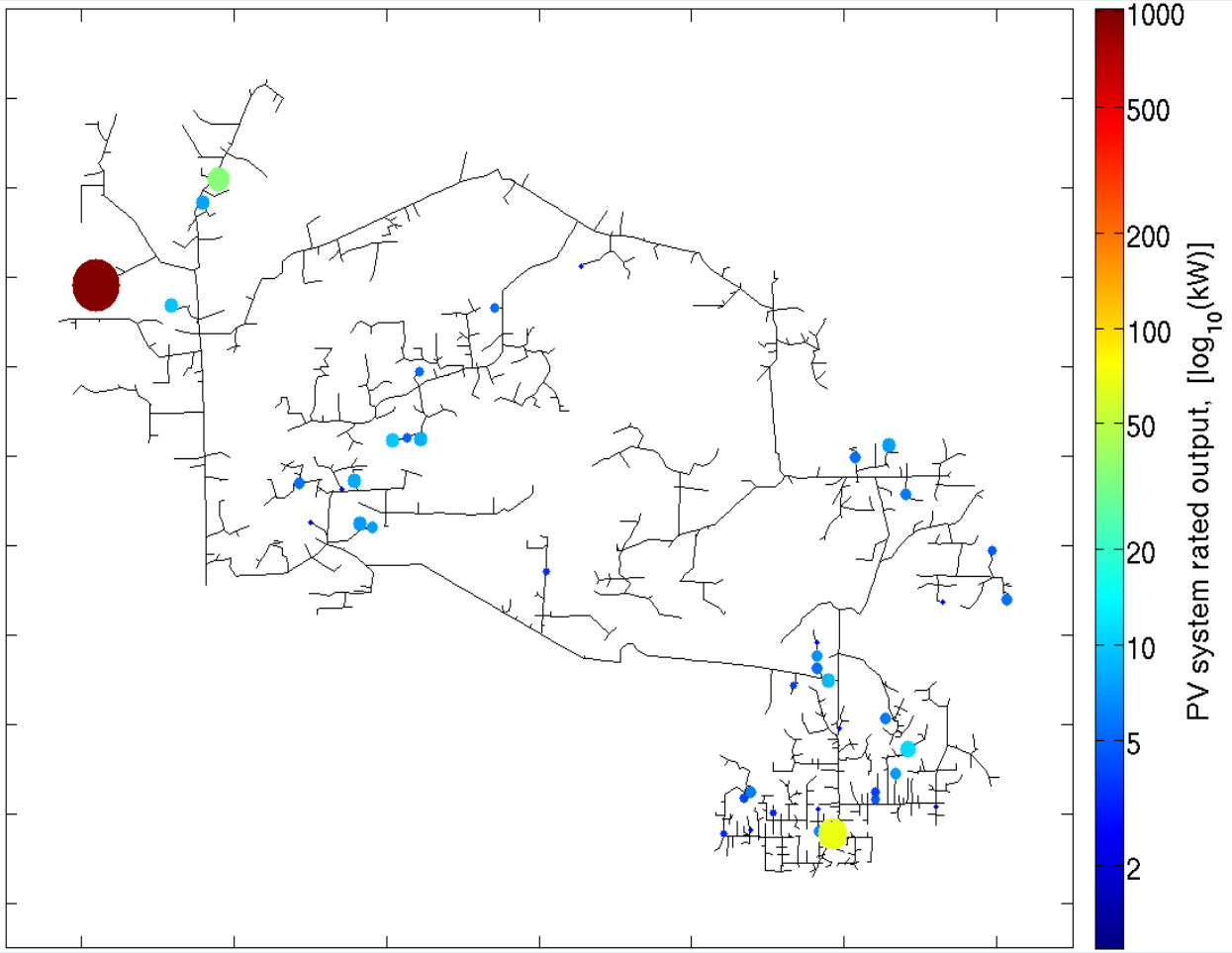
45 PV generators (actual)

PV ID	Power, kW	PV ID	Power, kW
1	3	24	5
2	1.9	25	2.5
3	3.7	26	2.5
4	5.4	27	7.5
5	6	28	6.835
6	2.4	29	6.8
7	65	30	9.2
8	1.1	31	4.68
9	4.3	32	7.8
10	3.6	33	3.152
11	1.5	34	5
12	2.9	35	7
13	3.5	36	5.4
14	5	37	4.3
15	6.472	38	999
16	2.4	39	998.9
17	8.28	40	8.8
18	2.5	41	7.1
19	5.4	42	4.8
20	6.7	43	4.8
21	10.4	44	2.4
22	2.2	45	33.2
23	5.1		



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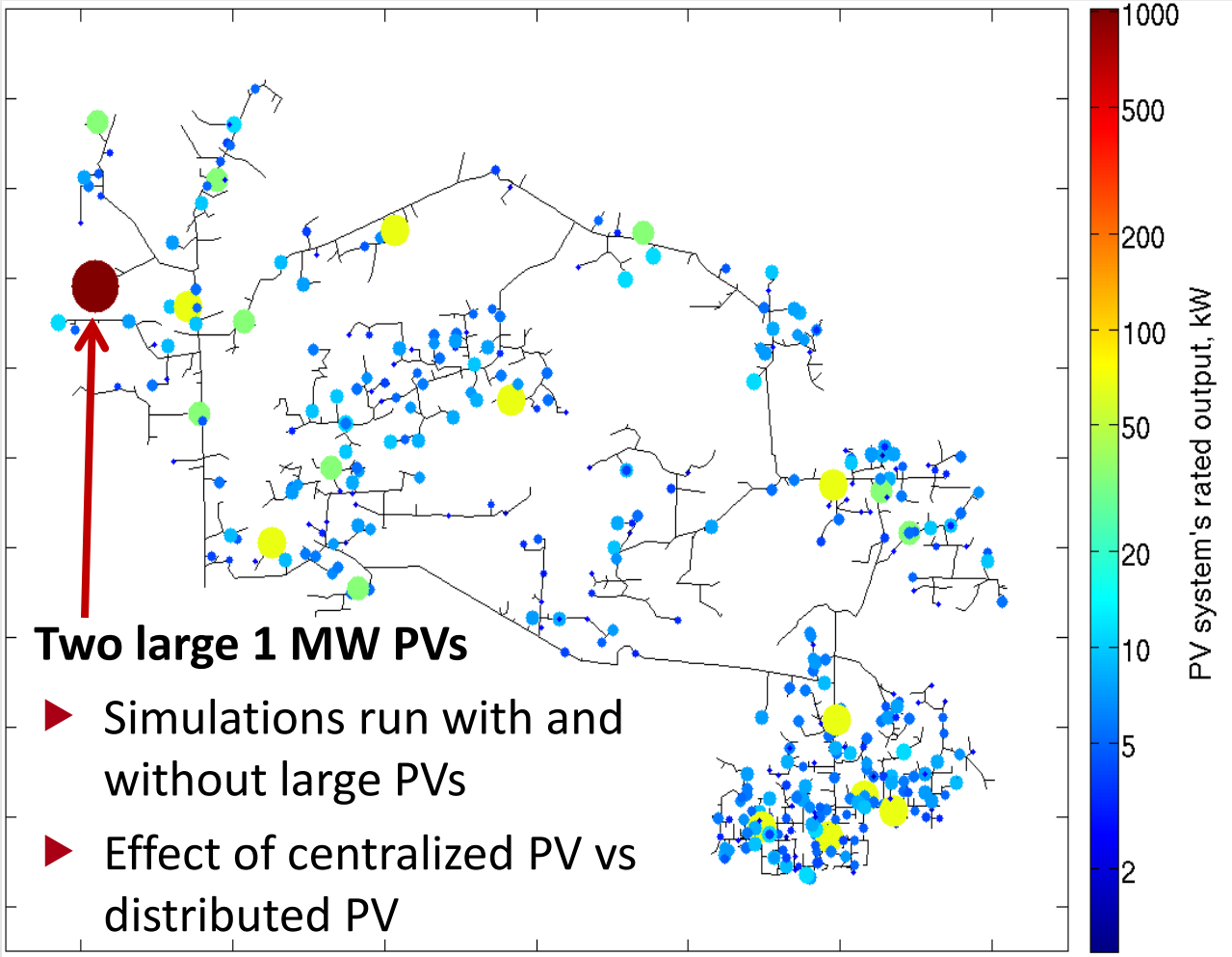
432 PV generators (future scenario)



Two large 1 MW PVs

- Simulations run with and without large PVs
- Effect of centralized PV vs distributed PV

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Disaggregating PV Generation & Load

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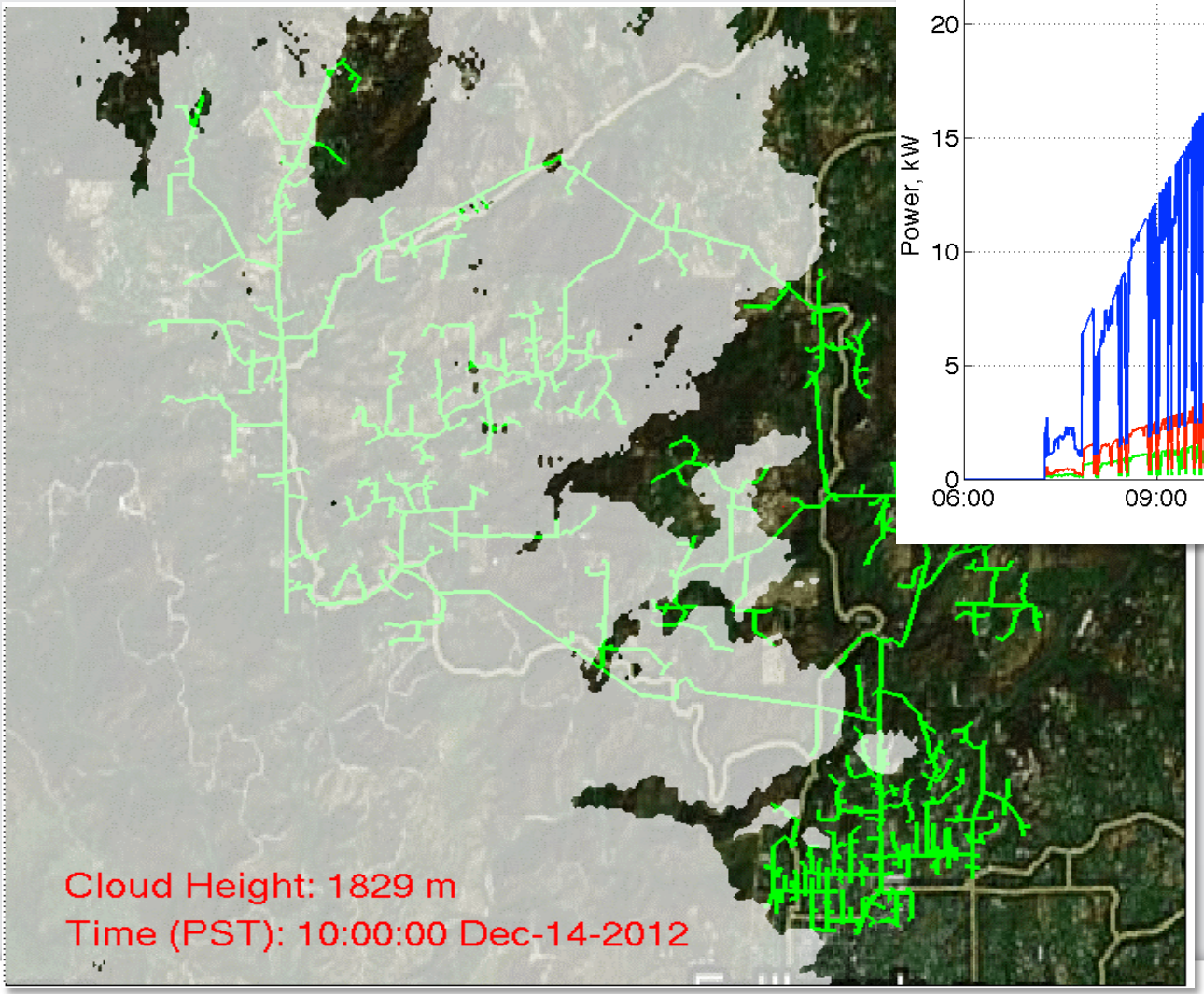
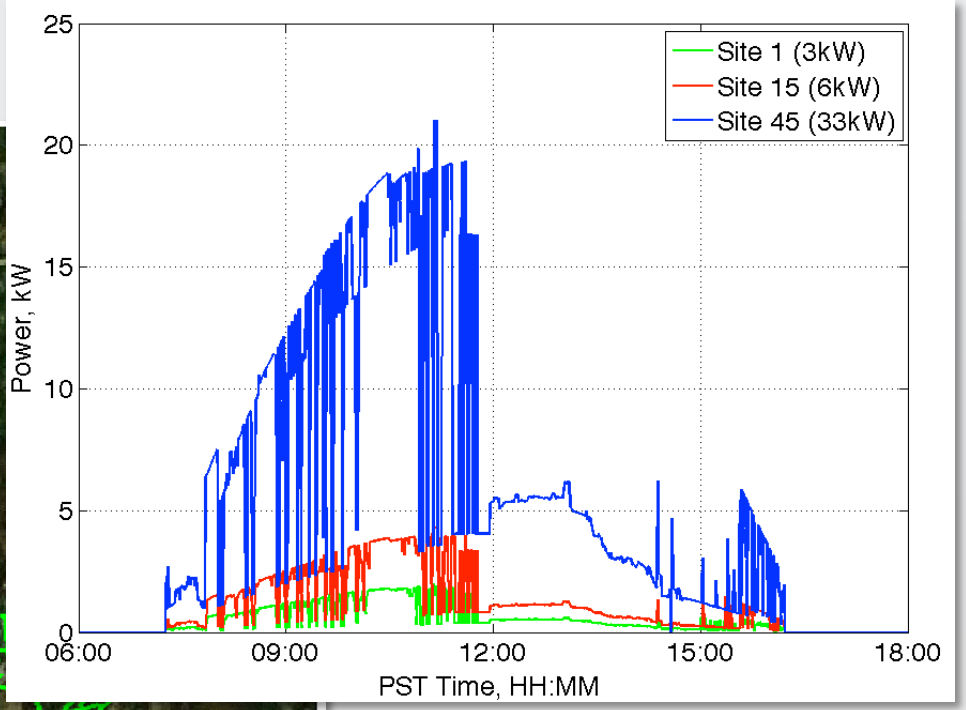
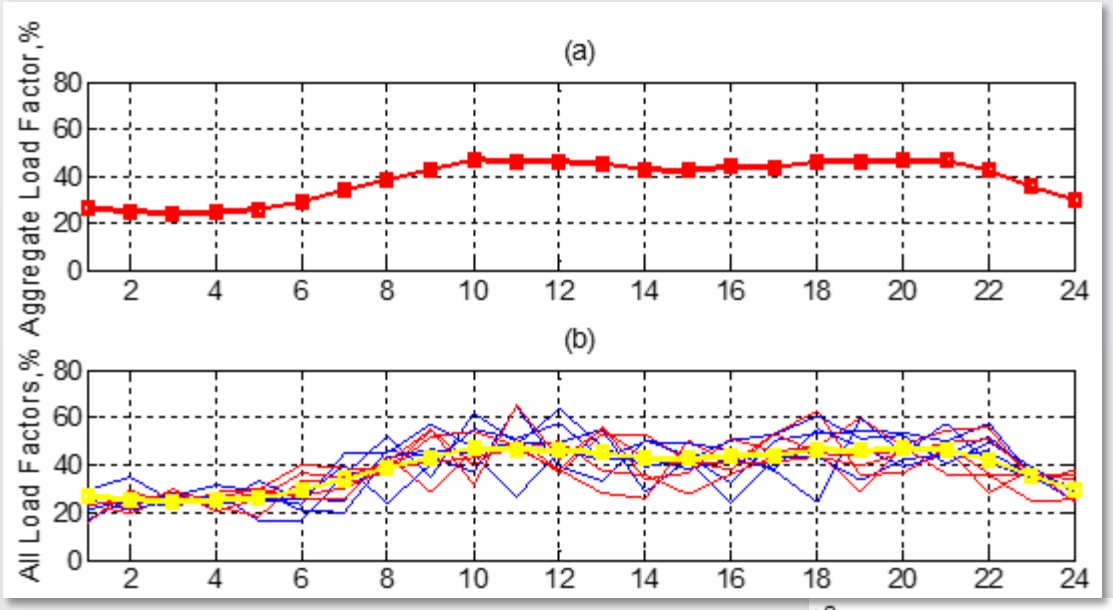
Disaggregating PV generation



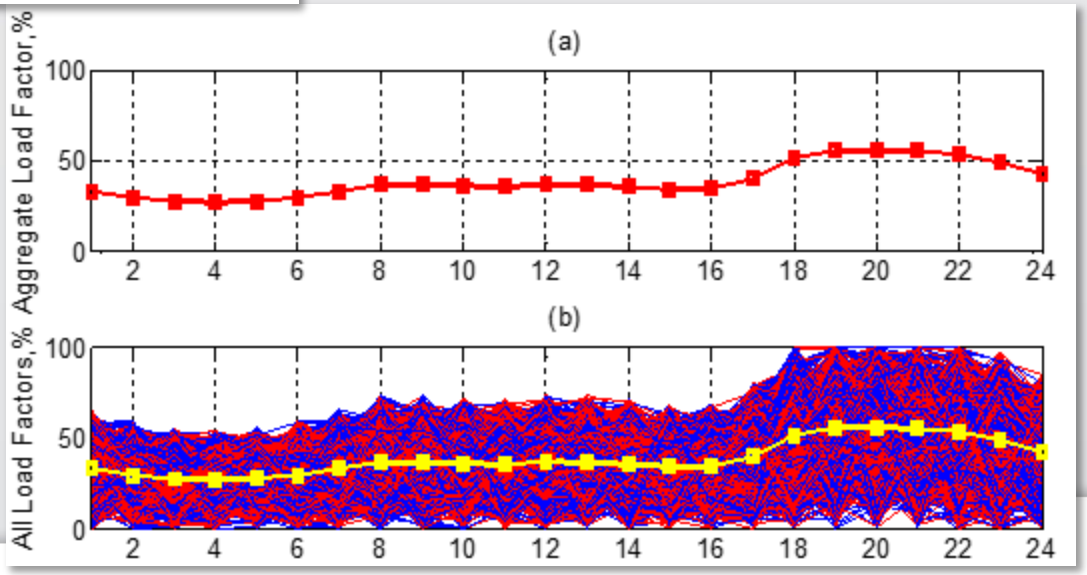


Disaggretating Loads



Disaggregating 10 loads (shown for illustrative purpose)

Disaggregating all residential loads used in our simulation



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Simulation Description & Results

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Simulation Scenarios

1. **Low (actual)** penetration of small PV **w/ 2 MW PV**
2. **Low (actual)** penetration of small PV **w/o 2 MW PV**
3. **High** penetration of small PV **w/ 2 MW PV**
4. **High** penetration of small PV **w/o 2 MW PV**

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Simulation Cases

Case #	Load Aggregated	PV Aggregated	Resolution	Sky Condition
0	Yes	Yes	1 h	Cloudy to Overcast
1	Yes	Yes	30 sec	Cloudy to Overcast
2	No	Yes	30 sec	Cloudy to Overcast
3	Yes	No	30 sec	Cloudy to Overcast
4	No	No	30 sec	Cloudy to Overcast
5	No	No	1 h	Cloudy to Overcast
6	No	Yes	30 sec	Clear

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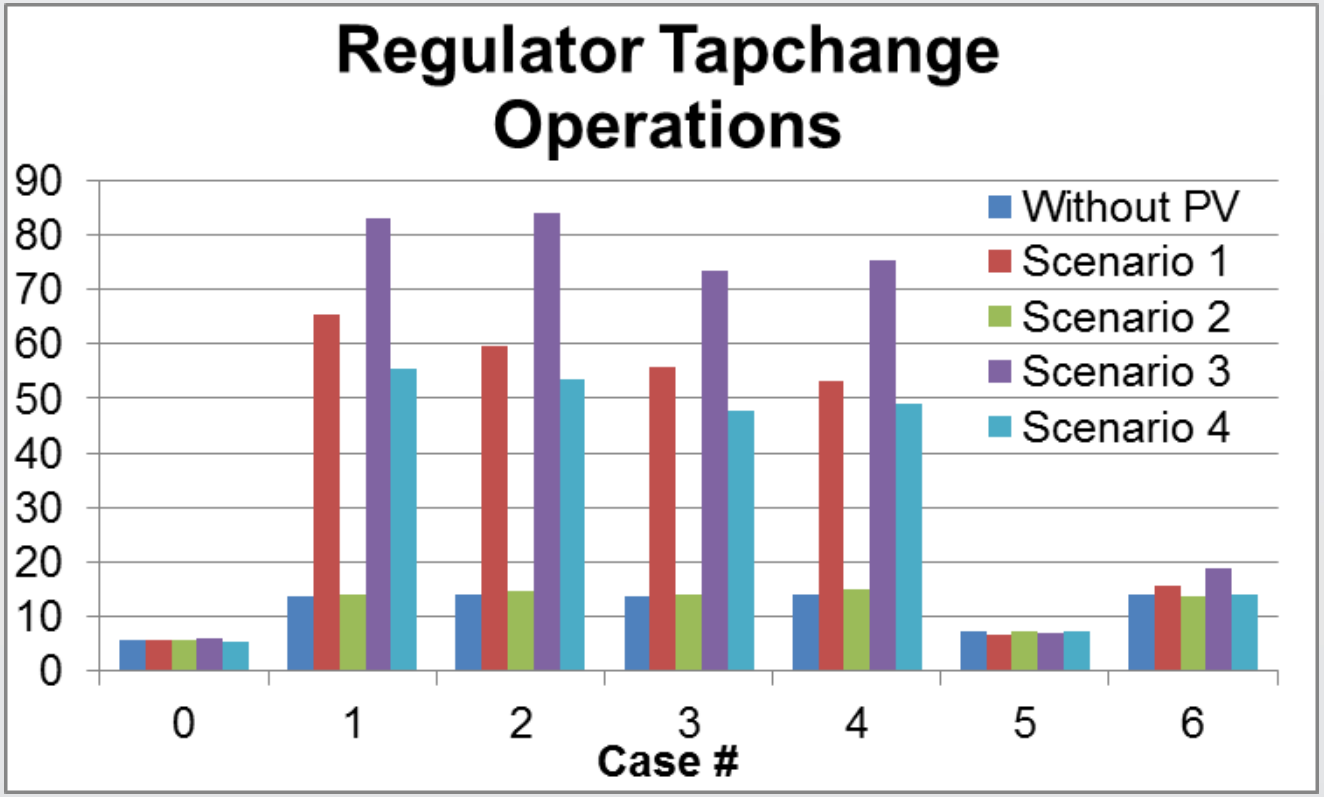
Selected Results



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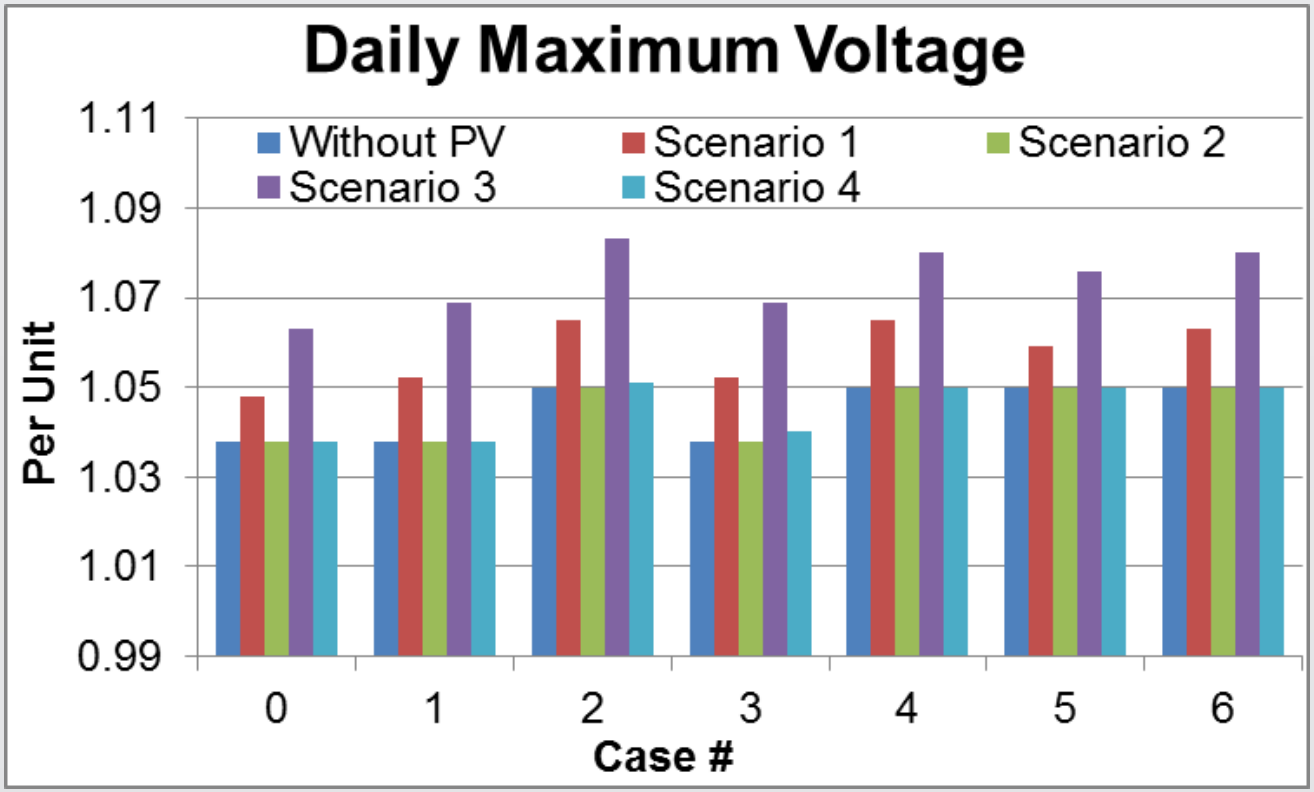
Selected Results



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Conclusions

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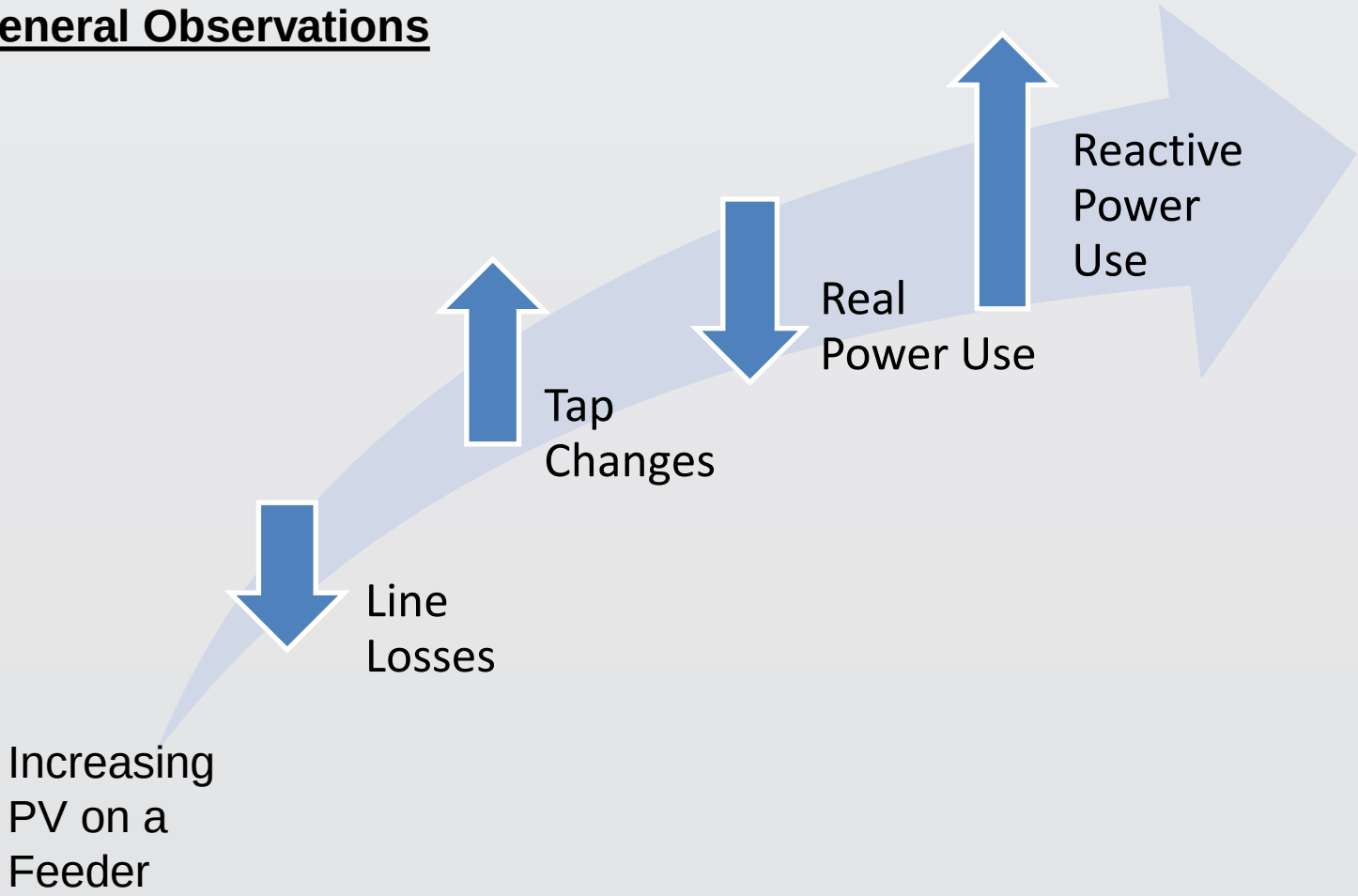
Selected Conclusions

General Observations



Graph by Stephan Barsun

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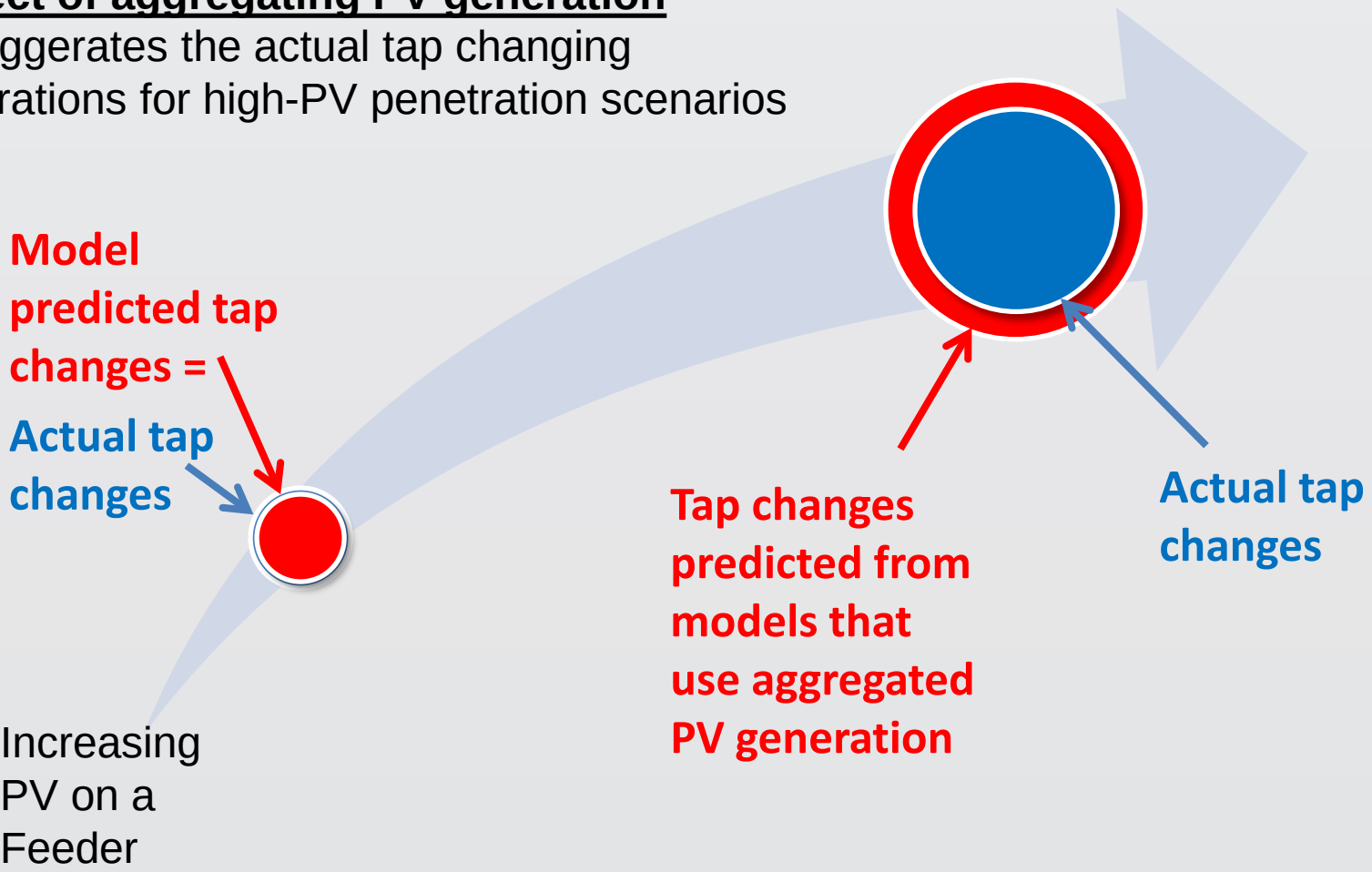
Selected Conclusions

Effect of aggregating PV generation

Exaggerates the actual tap changing operations for high-PV penetration scenarios



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Selected Conclusions

- **Disaggregating loads matters**, but no clear trend regarding whether this results in an increase or a decrease of the number of tap changing operations.
- **Distributed PV**: Voltage regulators that may exist on feeders to which a large amount of PV is added are likely capable of keeping the voltages along the feeder within permissible limits.
- Adding "x" kW of **centralized PV** to feeder is more likely to cause **overvoltages** compared to adding "x" kW of **Distributed PV**.

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Backup

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Detailed Conclusions

1) PV reduces line losses: The presence of PVs significantly reduces line losses on the feeder. In the low PV penetration Scenario 1, line losses are reduced by about 8% during cloudy days and 14% during a clear day. In the high PV penetration Scenario 3, line losses are reduced by about 11% and 19% during clear days and cloudy days, respectively. The losses are even further reduced when confining the time frame of the comparison to the daylight hours (up to 50% for the high PV penetration Scenario 3 during a clear day). We attribute the reduction of line losses to the fact the PV generation is much closer to the load compared to the no PV scenarios in which the power is supplied from the substation. On the other hand, the line losses for the low PV penetration Scenario 2 are very similar to the line losses for the no PV scenario. Note that our simulations do not account for transmissions losses that occur during the transfer of power from the plant to the substation. Accounting for these losses would increase the difference between losses without PV on the system and losses with PV on the system even more.

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Detailed Conclusions

2) Distributed PV vs. centralized PV: The PV penetration levels in Scenario 1 and Scenario 4 are similar (20% and 25%, respectively). The main difference is that Scenario 1 has two large 1 MW PV system located close together which constitutes nearly 90% of the total PV in the system. On the other hand, Scenario 4 does not contain large PV installations and the numerous smaller PV installations were more-or-less evenly distributed along the feeder. For the centralized PV Scenario 1, the tap changing operations were slightly more frequent and the line losses were larger compared the distributed PV Scenario 4. It is important to note that this tendency is not necessarily a general conclusion that applies to all feeders, but it shows that the distribution of the PV on the feeder has a significant impact on the both the tap changing operations and the losses.

The maximum voltage on the feeder for the no PV scenarios and the PV scenarios without the large PV installations (Scenarios 2 and 4) are essentially identical (1.05 pu). On the other hand, the maximum voltages in the centralized PV Scenarios 1 and 3 are significantly higher than in the no PV / distributed PV Scenarios (up to 1.08 pu). This indicates that the voltage regulators that exist on the investigated feeder are capable of keeping the voltages along the feeder within permissible limits – even if the number of distributed PV is increased tenfold. On the other hand, centralized PV on the feeder is much more prone to cause overvoltages – in particular if voltage regulators are not strategically placed to accommodate the PV concentration on the feeder. Note that, technically, PV inverters can be utilized to regulate the voltage on the feeder thereby potentially alleviating over and undervoltage issues on the feeder. However, IEEE 1547 does currently not permit the use of distributed generation for voltage regulation.

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Detailed Conclusions

3) PV increases operation of tap changers significantly – in particular during cloudy days: Tap changers during cloudy days in the high PV penetration Scenario 3 (41% penetration) are operating about 70 to 80 times each day (depending on the simulation case) which is significantly higher than the number of tap changer operations for the no PV and low PV penetration Scenario 2 (about 13 operation for both scenarios) and the clear-day simulation case 6 (between 12 and 19 operations, depending on the scenario). This indicates that tap changing operations during cloudy days will significantly increase if PV penetration levels are high, which will substantially increase maintenance costs and life-cycle costs of voltage regulators. On the other hand, for low PV penetration levels and during clear days, the tap changing operations is not impacted much. Note that the conclusions above came out of results from our high-resolution (30 seconds) simulations. Our simulations with low-resolution (one hour) data were not suitable to resolve any of these differences – in fact the number of tab changing operations from the low-resolution results were around five for all PV penetration scenarios, which results in a large error for the high PV penetration scenarios where the number of tap changing operations reached above 80.

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Detailed Conclusions

4) Low temporal resolution data vs. high temporal resolution data: Using low resolution data underestimates tap changing operations significantly in high PV penetration scenarios. In our simulations, the increase in tap changing operations for high PV penetration levels was only observed when more accurate high resolution data (30 second time step) were used as input to the model. Simulations with low-resolution data (one hour time step) did not show the increase in tap changing operations. This indicates that it is important to use high resolution data when evaluating tap changing operations for high PV penetration scenarios.

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Detailed Conclusions

5) Effect of disaggregating PV irradiances: For the >20% PV penetration Scenarios 1, 3, and 4, a comparison of the number of tap changing operations for cases 1 and 3 (aggregated/disaggregated PV; loads aggregated in both cases) and cases 2 and 4 (aggregated/disaggregate PV; loads disaggregated in both cases) shows that disaggregation of the PV generation does reduce the number of tap changing operations significantly (30 to 70%). This indicates that aggregating the PV in simulations may exaggerate the actual tap changing operations substantially that would occur on a real life system.

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Detailed Conclusions

6) Effect of disaggregating load profiles: For the >20% PV penetration Scenarios 1, 3, and 4, a comparison of the number of tap changing operations for cases 1 and 2 (aggregated/disaggregated loads; PV aggregated in both cases) and cases 3 and 4 (aggregated/disaggregate loads; PV disaggregated in both cases) shows that load disaggregation impacts the number of tap changing operations. However, there is no clear trend regarding whether disaggregating the loads results in an increase or a decrease of the number of tap changing operations.

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Detailed Conclusions

7) Net consumption of active power: For the >20% PV penetration Scenarios 1, 3 and 4, the active power net consumption of the distribution feeder, that is, the active power that needs to be supplied from the substation to support the load demand on the feeder, is significantly reduced. For example, for the high PV penetration Scenario 3, the daily reduction of net consumption due to the presence of PV leads to about 8-15% less energy demand for the feeder, depending on the sky condition. In other words, generation sources outside the feeder need to supply about 8-15% less energy to the feeder (not accounting for losses associated with the transfer of power from the plant to the substation). If these outside generation sources are fueled by conventional non-renewable resources (fossil and radioactive fuels), then this reduction leads to significant savings of these non-renewable resources.

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Detailed Conclusions

8) Net consumption of reactive power: Conversely to the previous conclusion, the reactive power net consumption of the distribution feeder is increased, that is, more reactive power is consumed on the feeder, which has to be supplied by generation sources or reactive compensation outside the feeder or at the substation. This is because the PVs, in particular at high penetration levels, increase the voltages on the feeder, which results in more power consumed by the loads on the feeder. The PVs in our simulation operate at unity power factor, that is, they provide active power, but no reactive power. Consequently, the net consumption of reactive power is increased. On the other hand, the net consumption of active power is reduced because the additional active power (due to the voltage increase) is supplied by the PV. Note that this result depends strongly on the load mix on the feeder – we modeled all loads as ZIP loads with 70% active power and 30% reactive power. Our interpretation of this result is that PVs can decrease the operating efficiency of loads if the utility does not make adjustments. However, the increased voltages on the feeder due to the PV gives the utility the opportunity to apply energy saving measures such as conservation voltage reduction, that is, the utility can lower the voltage at the substation during times of PV production and the power generated by the PV will keep the voltages along the feeder within permissible limits. This practice would be particularly effective if (1) the PV is evenly distributed along the feeder as this will avoid localized regions on the feeder that have undervoltage when the voltage at the substation is reduced and (2) during clear days as this would avoid sudden undervoltage conditions due to clouds. Lowering the voltage at the substation will decrease the reactive power net consumption and further reduce the active power that needs to be supplied from outside generation sources.

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Solar Resources and PV Modeling

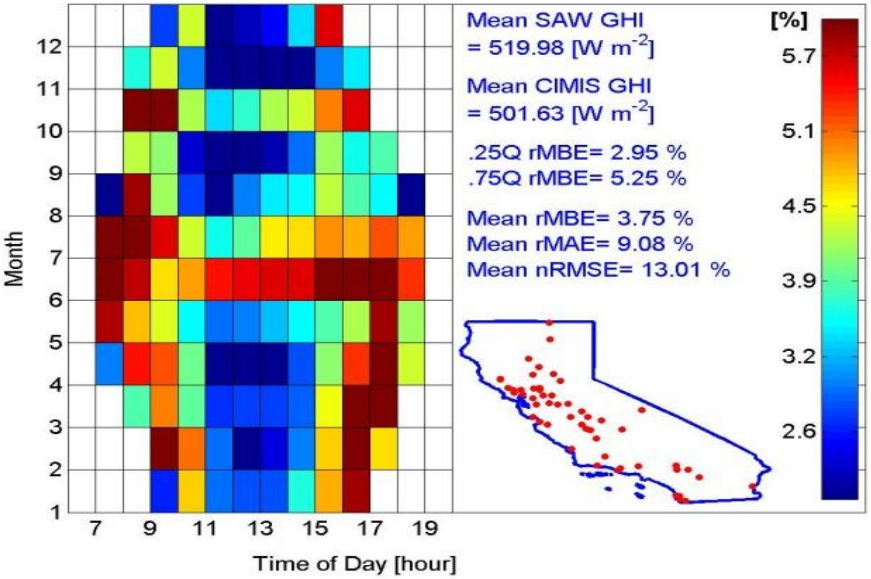
Topographic Horizon Database

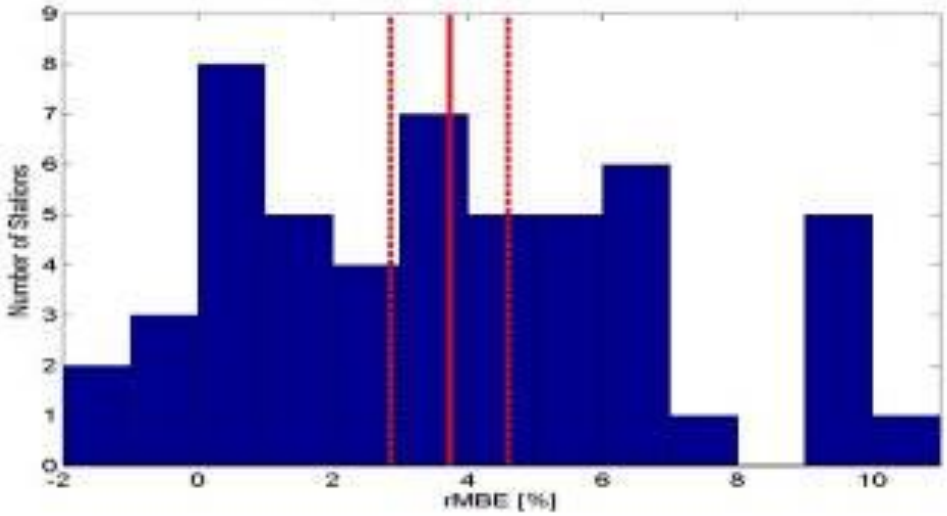
PV Performance Model

Soiling Model

Solar Resource Validation

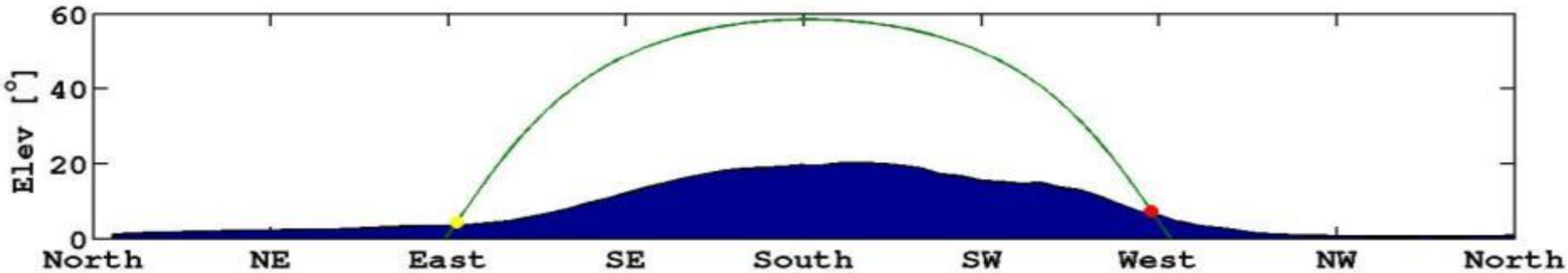
- Validated 1 km, 30 min solar resource data by CSI Grantee Clean Power Research.
- Added value through topographic horizon, soiling, and downscaling analysis.





Topographic Horizon Database

- Topographic shading reduces PV output and is commonly not considered by satellite or NWP solar resource models.
- Impact on PV generation generally benign, but can be a few % in mountainous areas.



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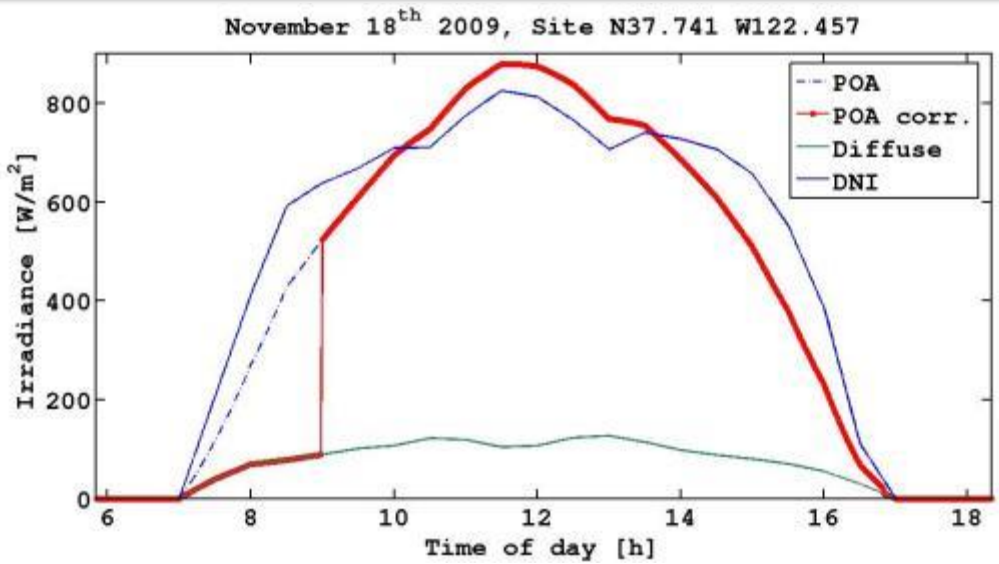
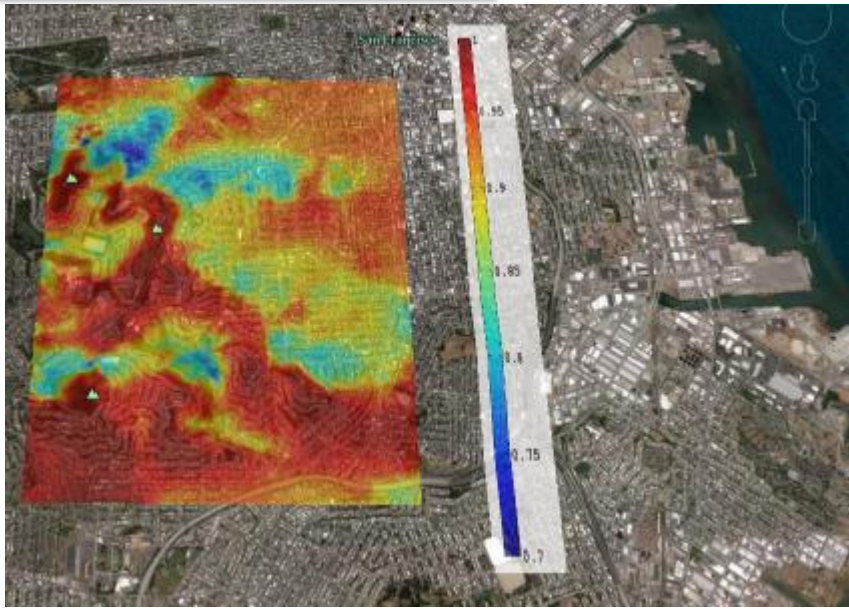
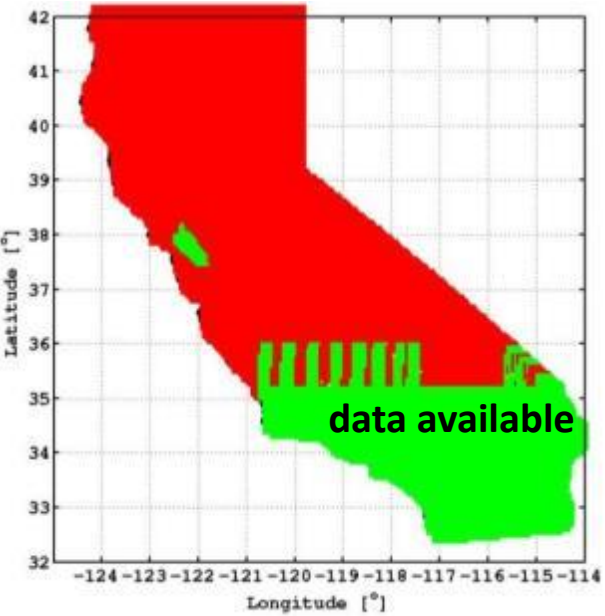
Case Study – Twin Peaks





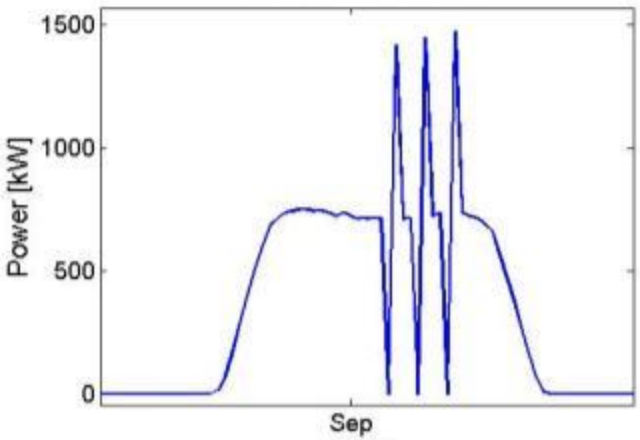


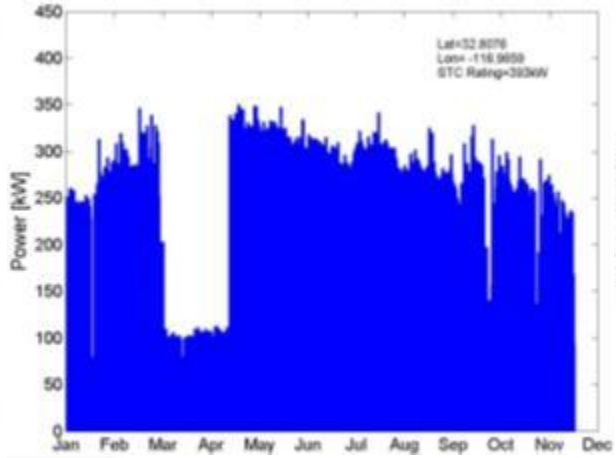
- Day length up to 30% shorter than unobstructed
- Annual losses usually less than 1%
- Data available for all high PV penetration regions with topography
- Horizon elevation in degrees as a function of azimuth
  - 30 m resolution
  - Every 5° azimuth
- Data integrated with 1 large monitoring firm and 1 large solar resource data provider

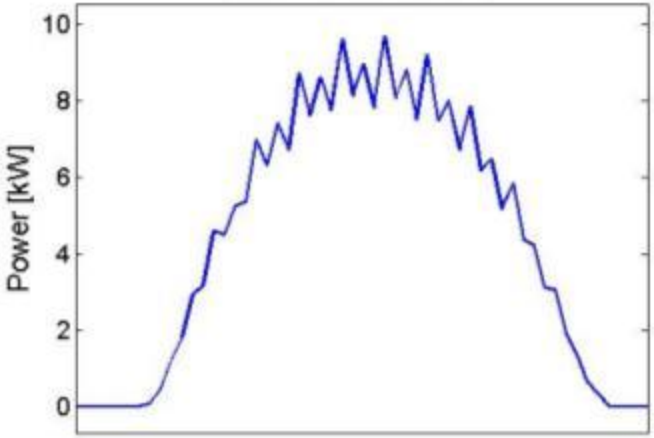
--> More accurate solar production estimates for Californians

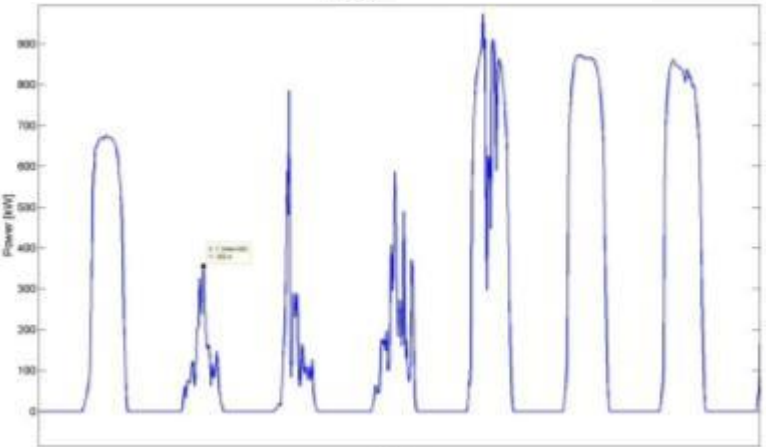
Quality-controlled 2009-2010 CSI PBI

- California Solar Initiative Performance-Based Incentive Program
- Catalogued a variety of phenomena not representative of irradiance

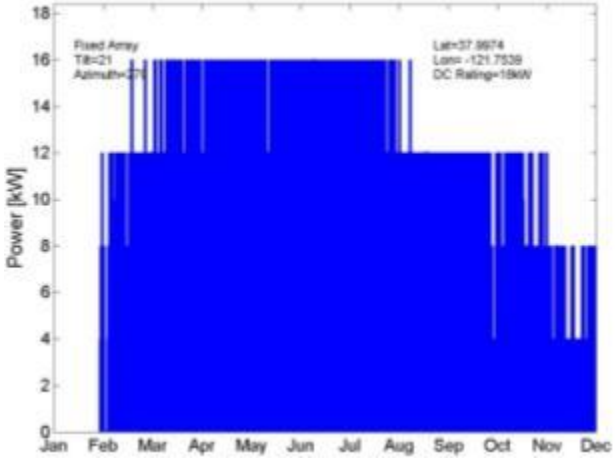






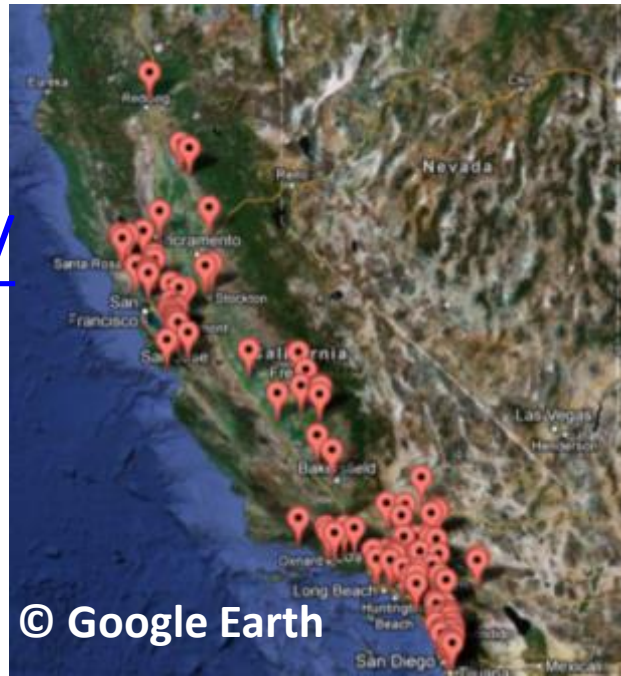


QC'ed dataset available upon request

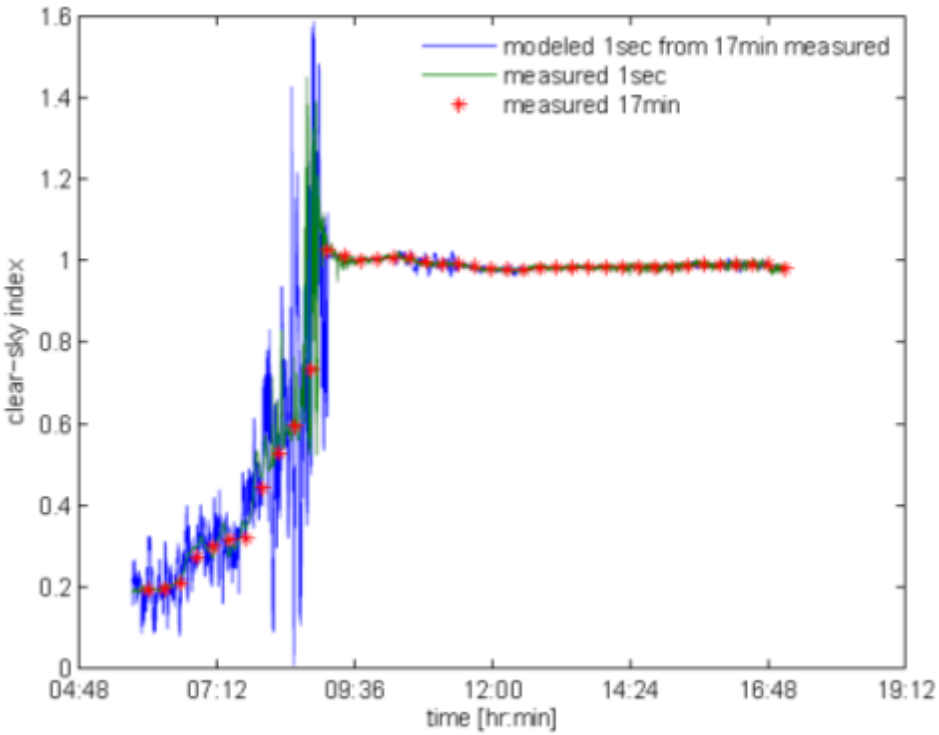


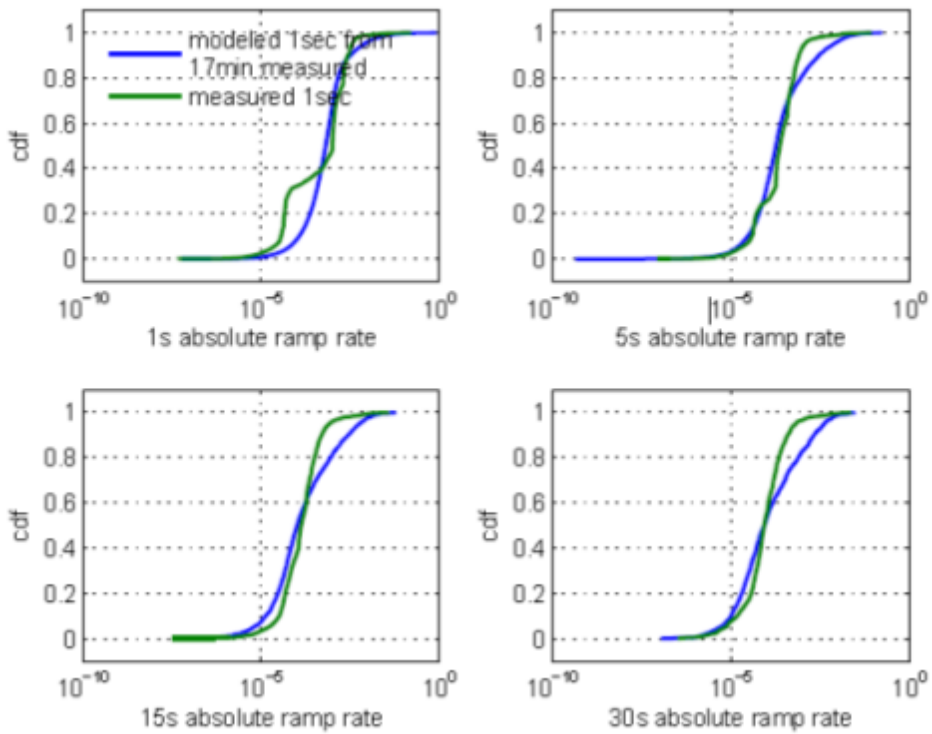
Downscaled CSI PBI Data to 1 sec

- High resolution PV data required for integration studies
  - Voltage variability impacts of PV exacerbated when assuming uniform output profiles for all sites on a feeder
- CSI data are averaged over 15 min
- Request 1 sec data at http://solar.ucsd.edu/datasharing/
- 365 days of 1 sec data per site
- 115 sites in California



Downscaling Example





- Statistical downscaling uses properties of resolved data (e.g. clear versus cloudy) to dynamically introduce fluctuations.
- Accurate match with observed ramp rates.

PV Performance Model

- Developed PV performance model
  - Irradiance on tilted surface
  - Panel temperature effect on efficiency
  - DC-AC conversion efficiency
  - MPP efficiency
- Calibrated model parameters using CSI PV performance data
- Model available in MATLAB

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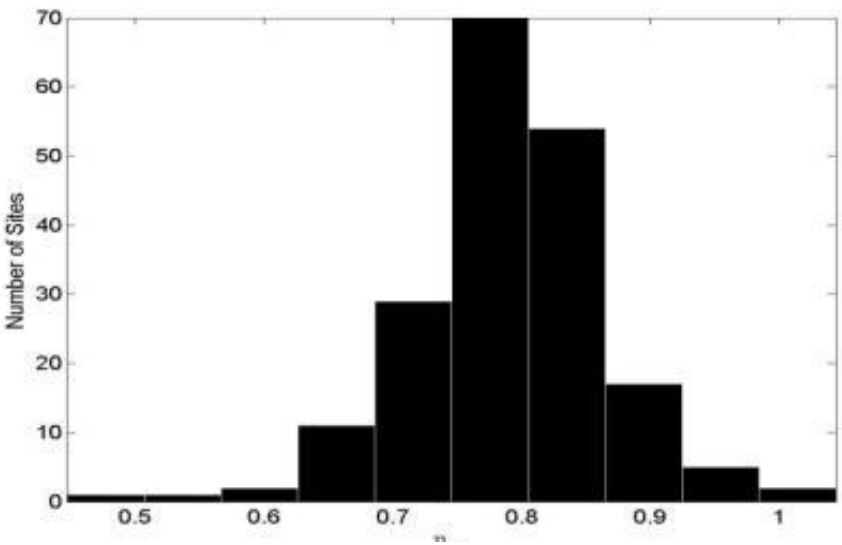
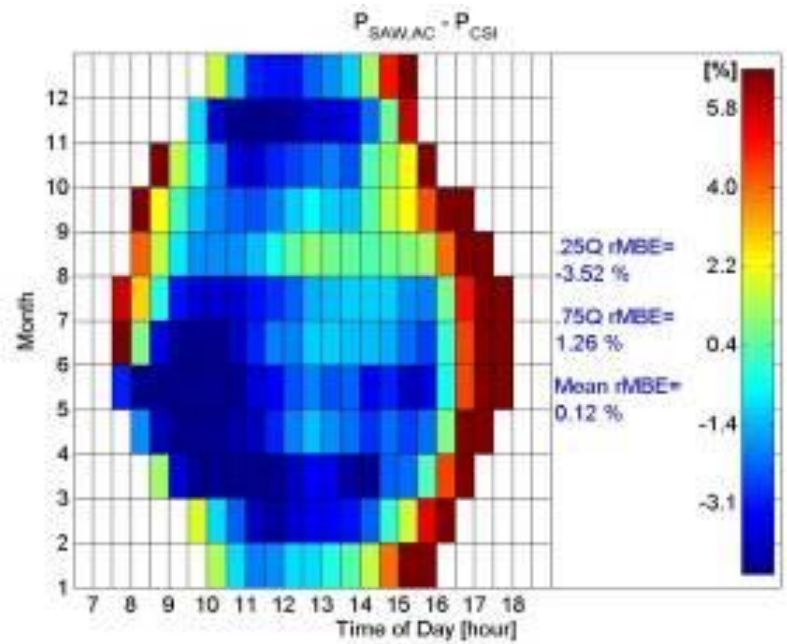
PV Performance Model - Results

- Average panel temperature coefficient 0.49 % / K
- Average de-rate factor: 21%
- Typical MAPE = 4.8% for 30 min average of 192 sites



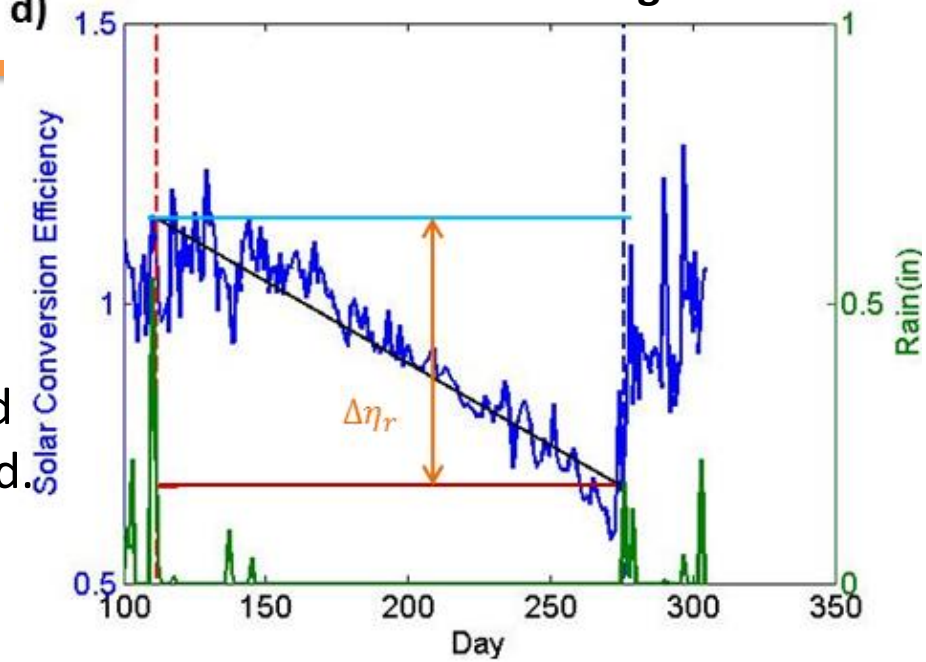
Annual 'Efficiency' (1 - Derate Factor)



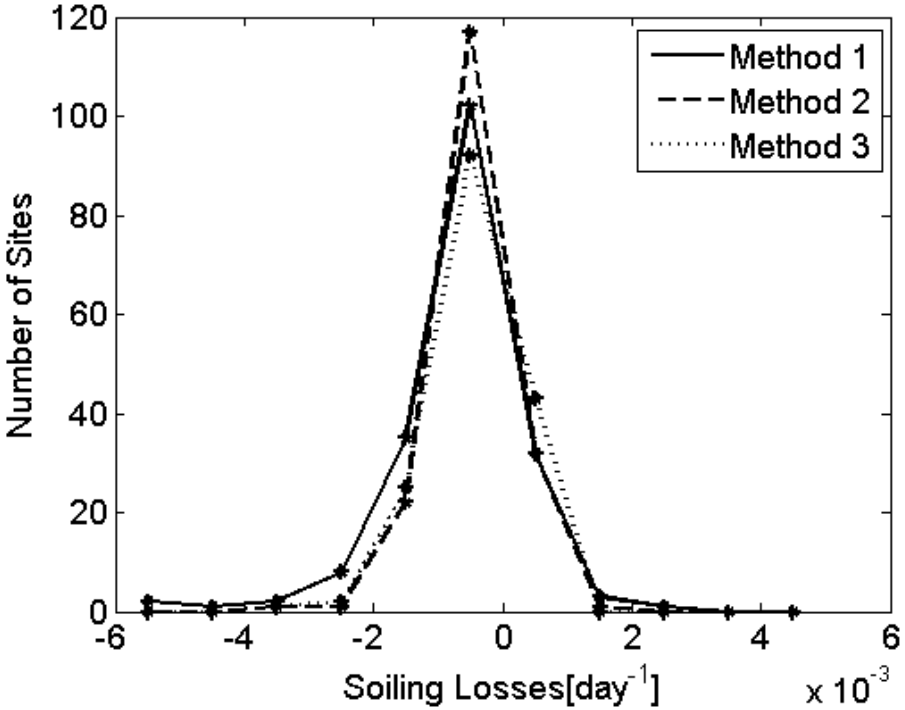
Soiling Analysis

Losses averaged 0.051% per day. Over an average summer drought of 145 days this results in a 7.4% loss in efficiency.
On average, the energy yield would have increased by 0.81% if they had been washed halfway through the summer drought period.

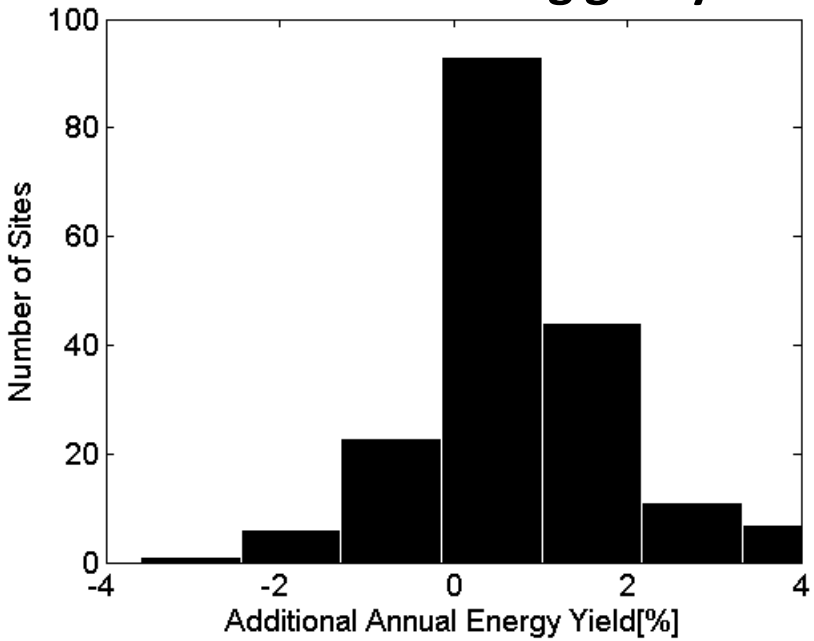
How did we obtain soiling losses?



Histogram of Soiling Losses



What does 1 cleaning give you?



PV Performance Model Conclusions

- Soiling impact on PV production generally small
  - Exceptions due to very localized dust emissions.
- PV performance model trued up to large amount of CSI metered data
  - Performs similar to PVWATTs
  - Increase flexibility and integration through MATLAB with small time steps

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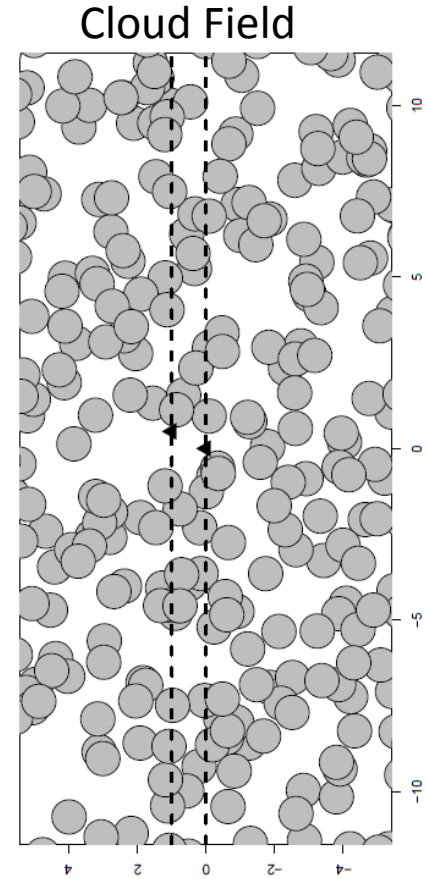
Solar Variability Modeling

PV variability model

Cloud motion sensor

Theoretical Foundation: Poisson Model



- Probability of two points k,l being covered by clouds

$$\mathbb{P}(P_k = P_l = 1) = \exp\left(-\lambda\left[2\pi r^2 - A\left(r, d_{k,l}\right)\right]\right)$$

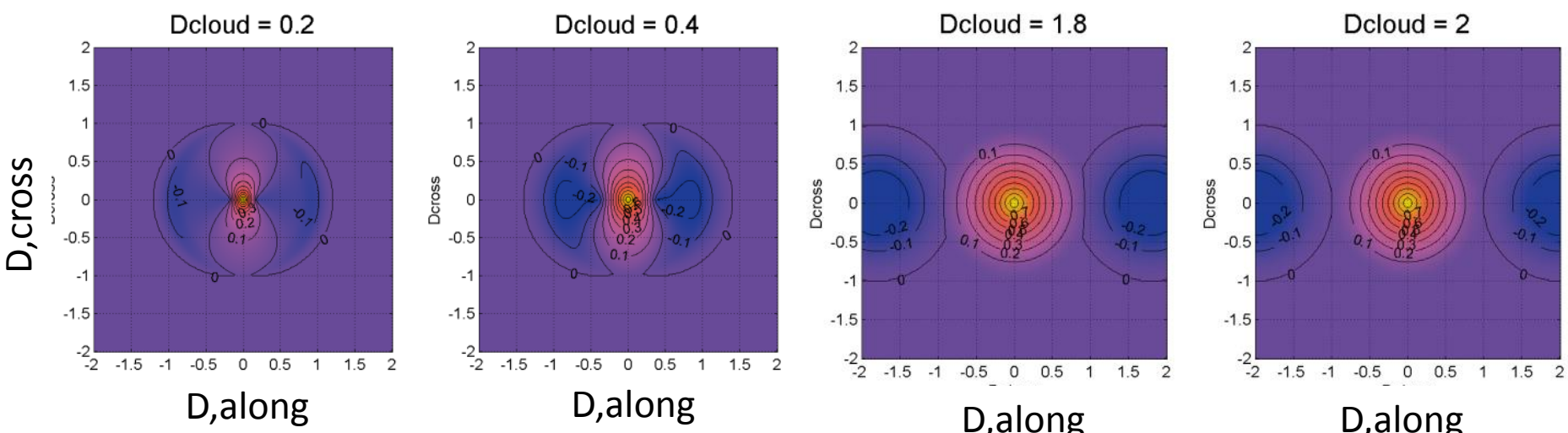
r: cloud radius, d: distance, λ: cloud cover

- Further manipulation shows that:

$$corr\left(RR_{k,\Delta t}, RR_{l,\Delta t}\right) = corr(\lambda_n, D_{along}, D_{cross}, D_{cloud})$$

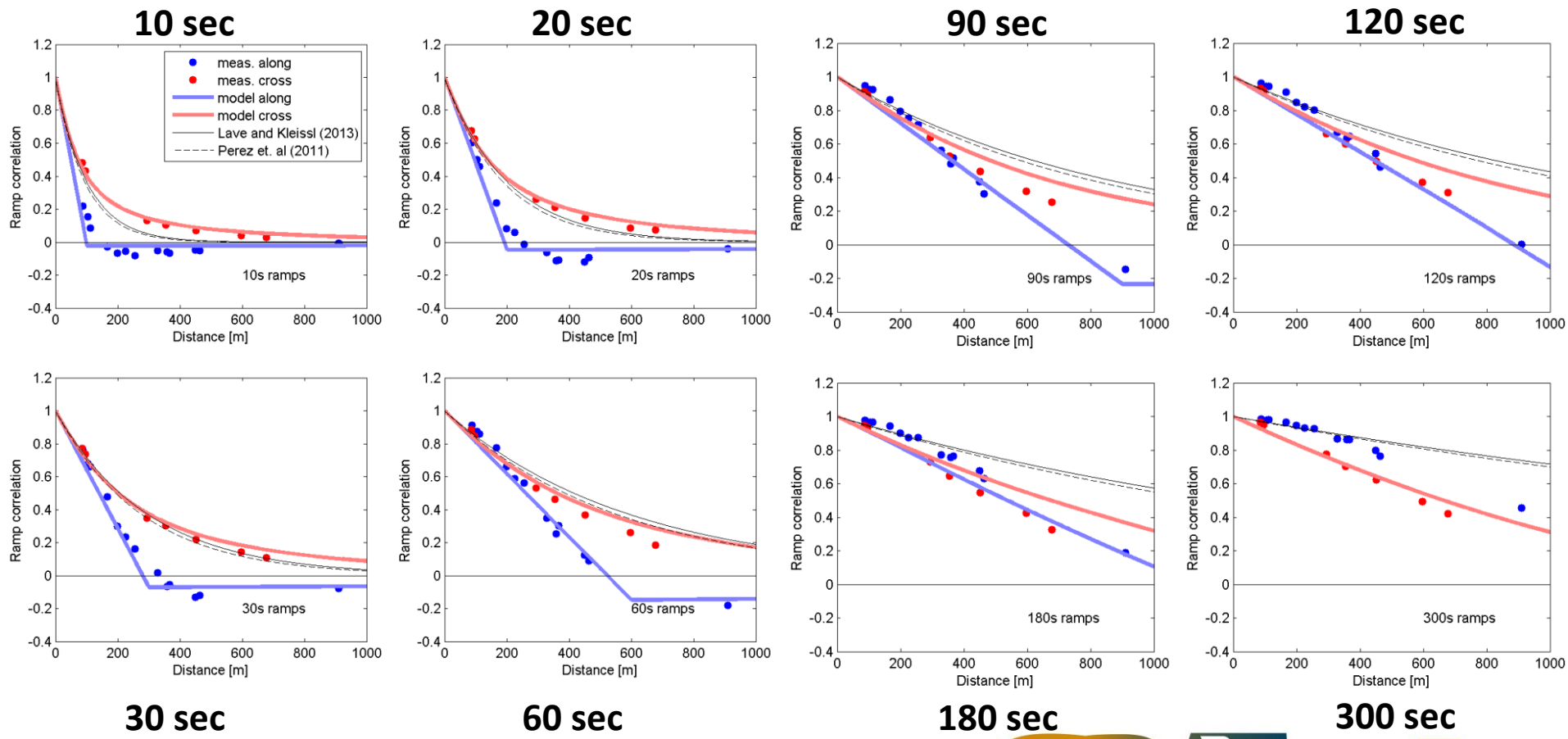
- Correlation Field

$$D_{cloud} = \frac{CS\Delta t}{2r}.$$



How does theoretical model fit experimental data?

- Excellent fit for short time scales.
- Deviations for 2+ minute ramps.



Analysis of measurements by Hinkelman (Solar Energy, 2013)

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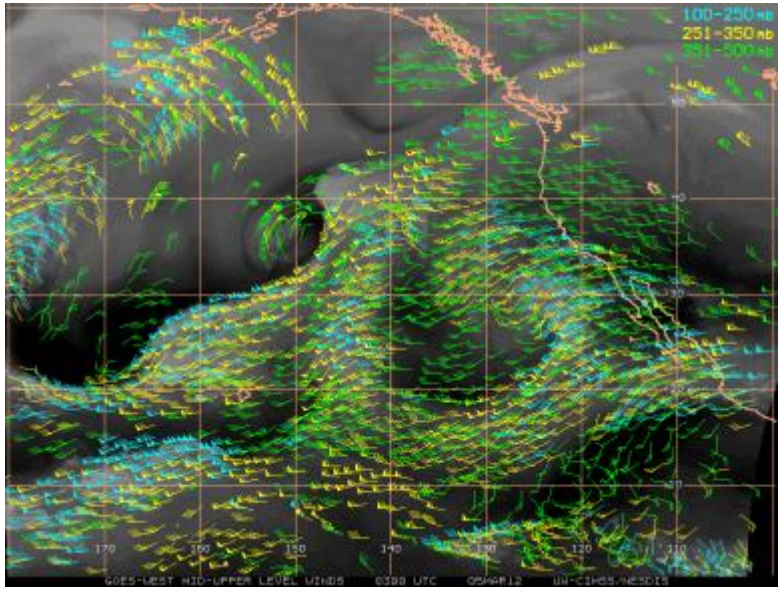
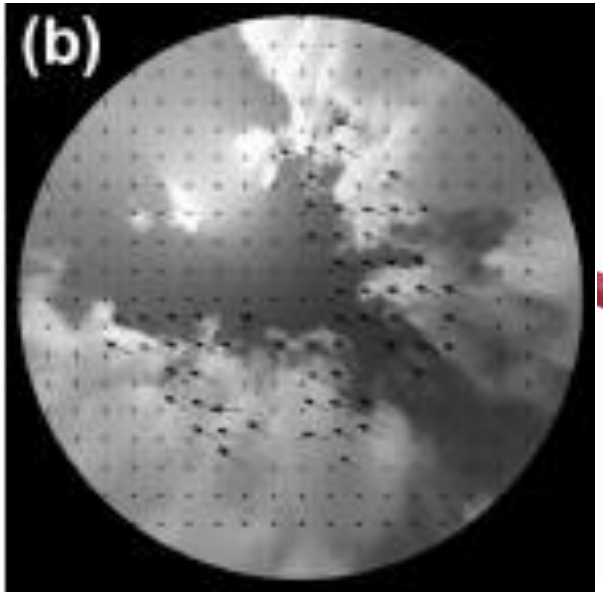
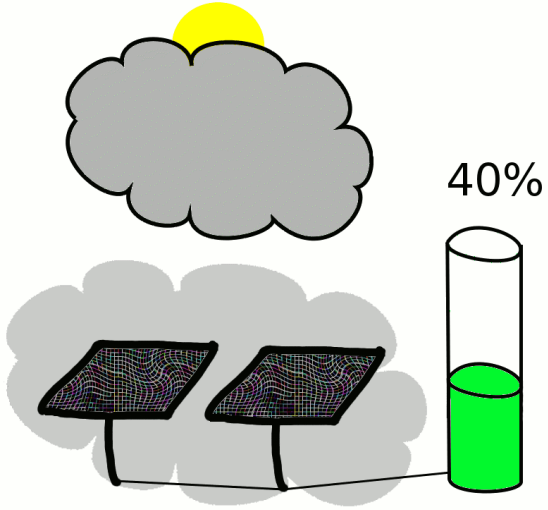
Cloud motion vector (CMV) estimation

Satellite



Sky Images





Applications:

- Solar forecasting through cloud advection
- Maximum ramp rate estimation.

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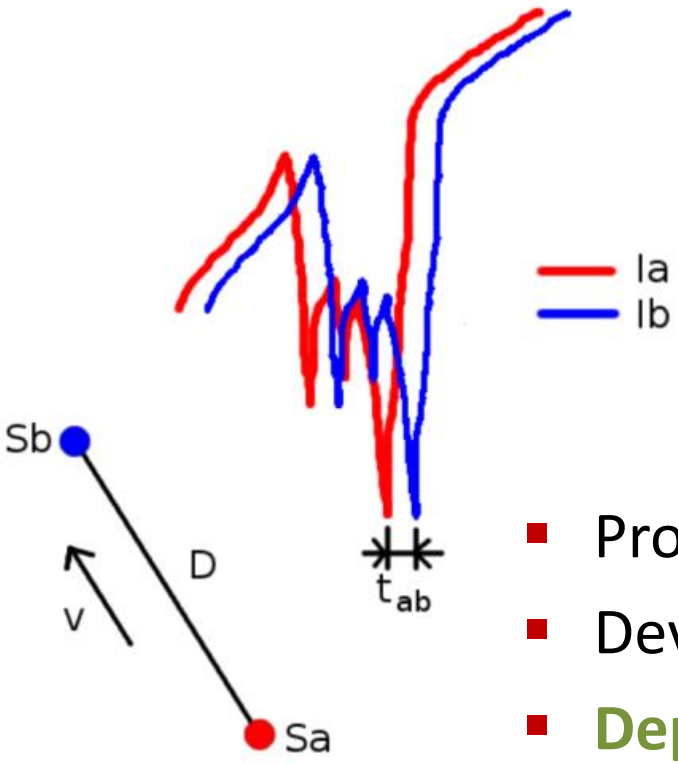
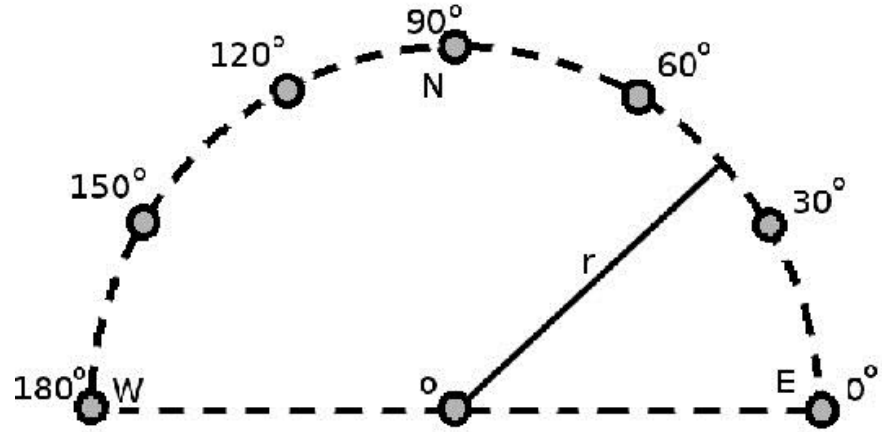
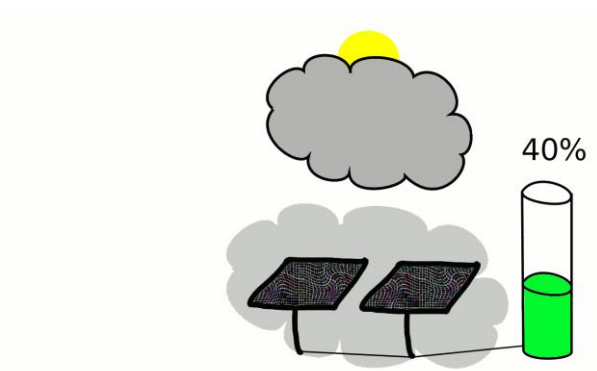
Sensor Development: Cloud Speed from Pairs of Solar Irradiance Measurements





- Provisional patent filed
- Developing commercializable product
- **Deployment at utility-scale solar power plants would improve intra-hour forecast accuracy**



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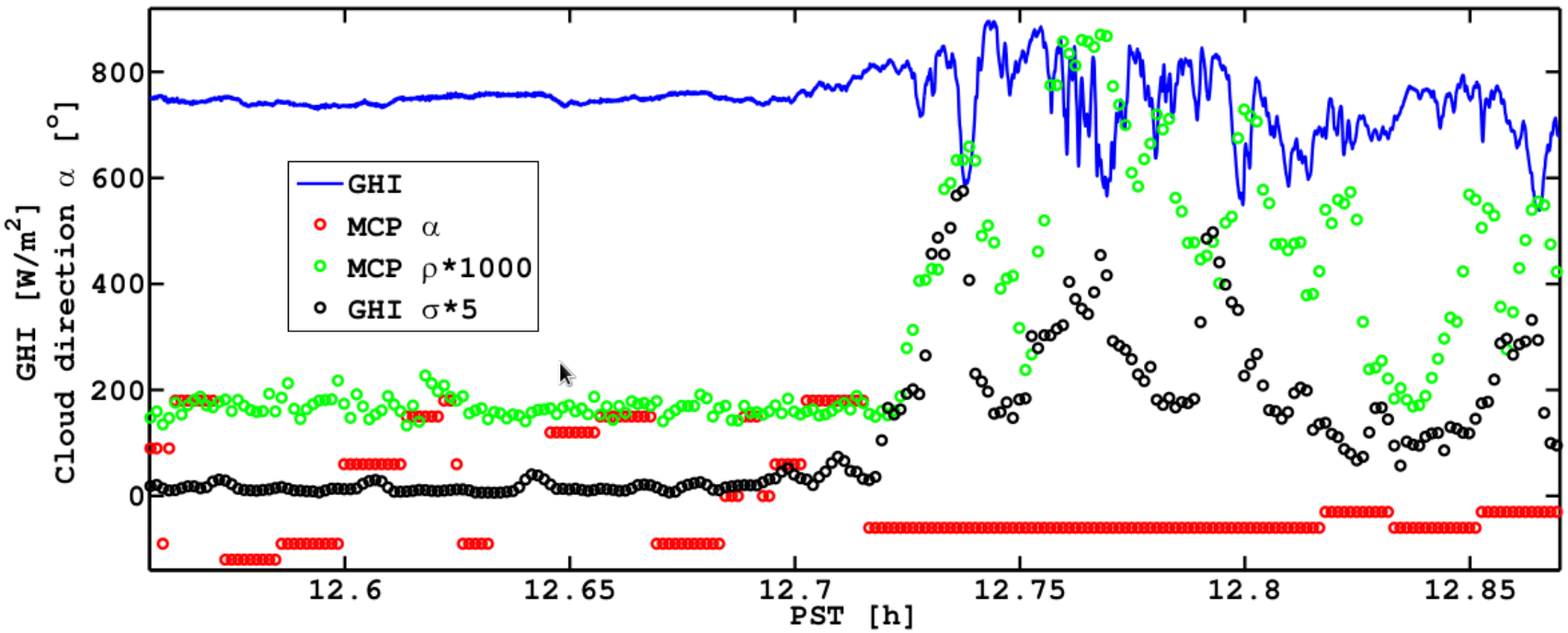
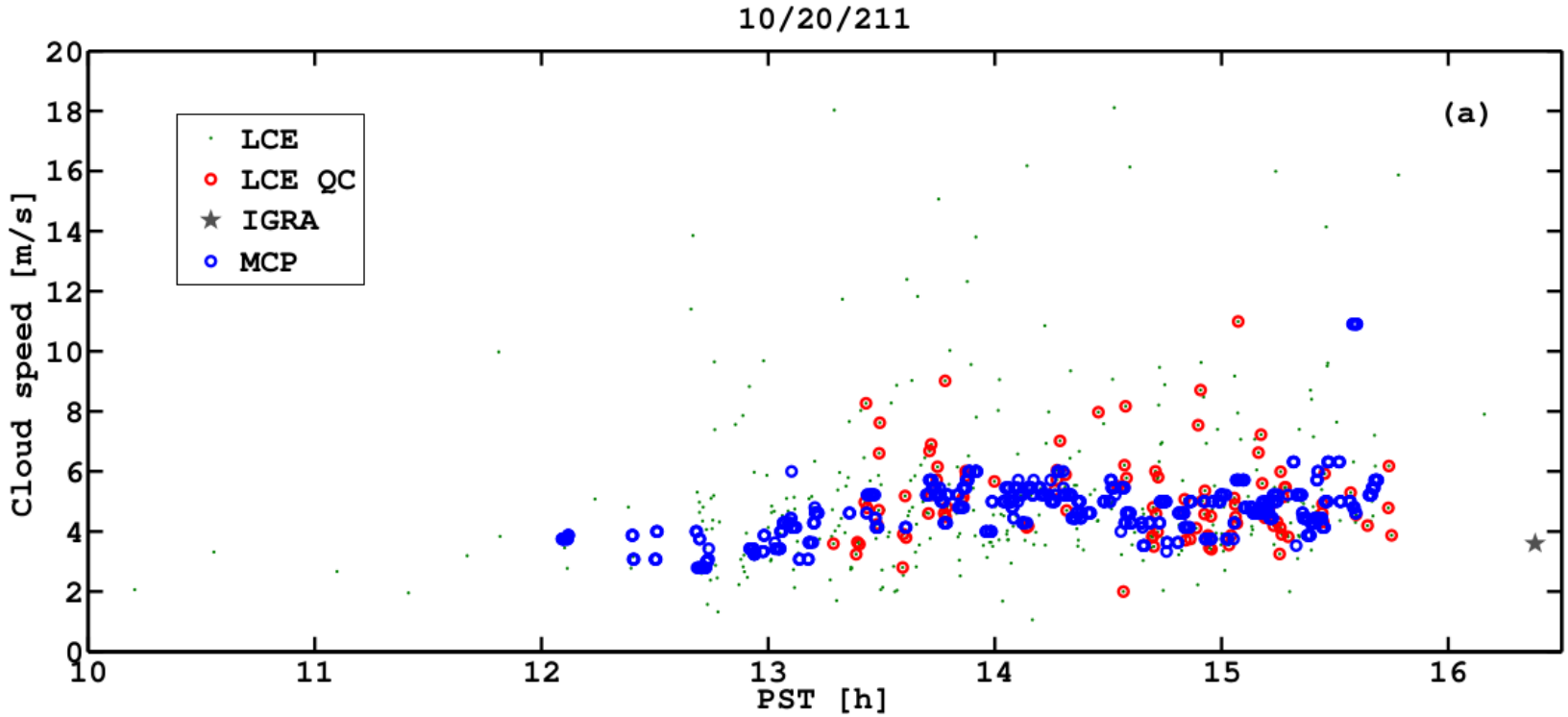
Sensor Measurements Depend on Irradiance Variability



Low GHI variability leads to random results, discarded after QC

High GHI variability leads to more consistent results

Cloud Speed Measurements



Similar results are obtained for both methods and radiosonde data

Cloud Motion Vector Conclusions

- CMVs facilitate PV variability modeling and intra-hour forecasting.
- Sensor developed to measure CMVs.
- Support solar PV integration.

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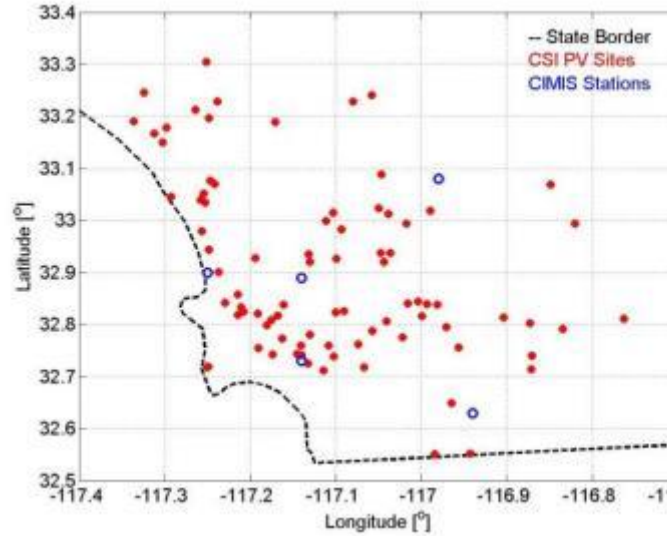
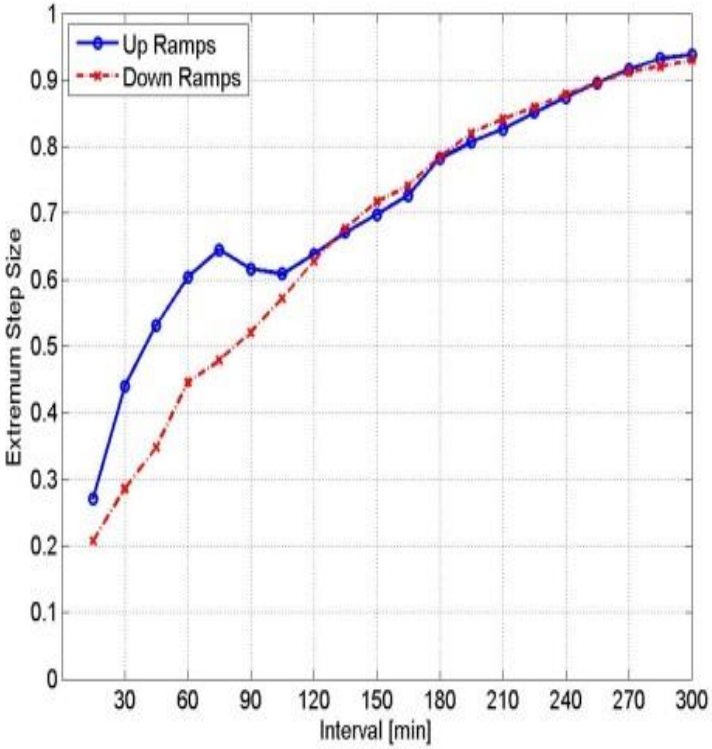
Aggregate PV ramp rate analysis

Most extreme PV generation ramps
in SCE, PG&E, SDG&E, CAISO

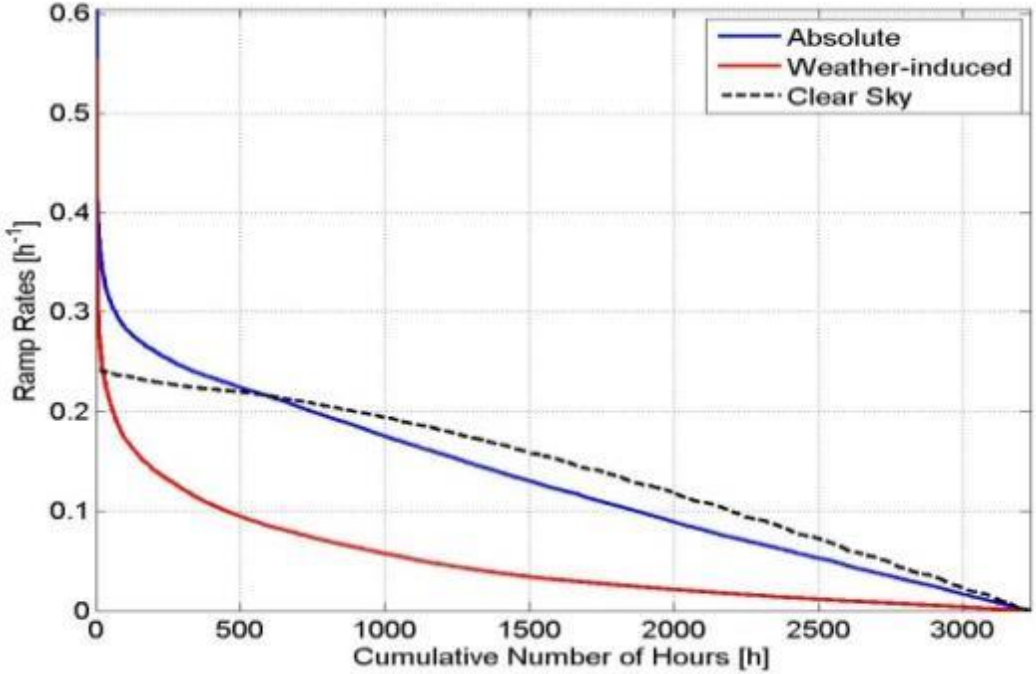
Ramp Rates for SDG&E

- Weather-induced RRs are wrt 30 day average daily cycle
- Largest ramp events are weather-induced



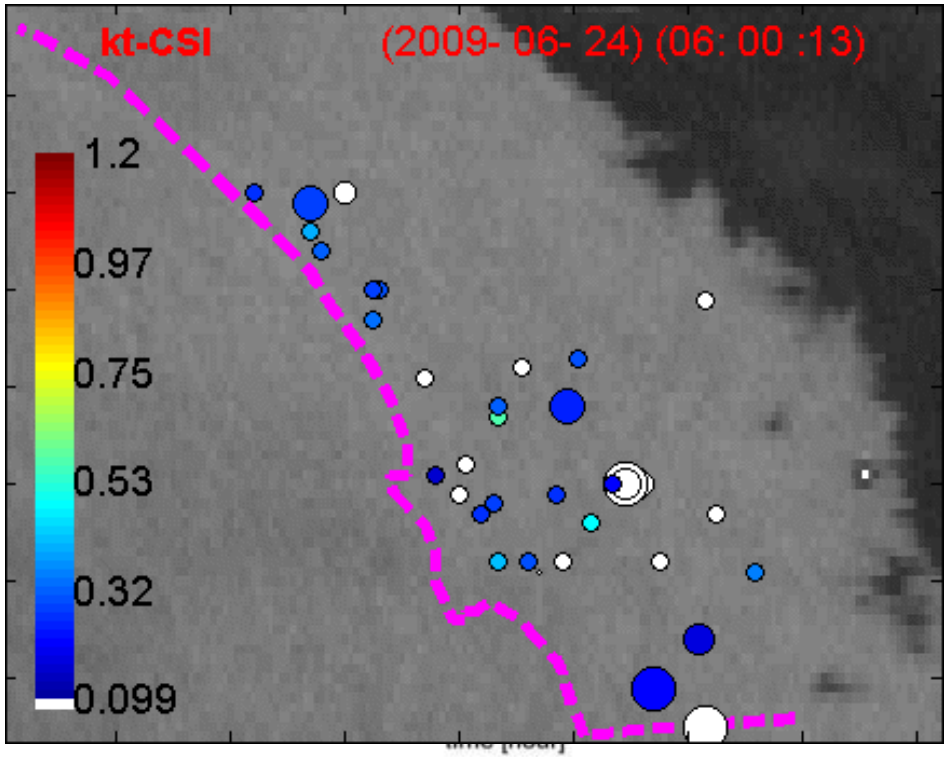


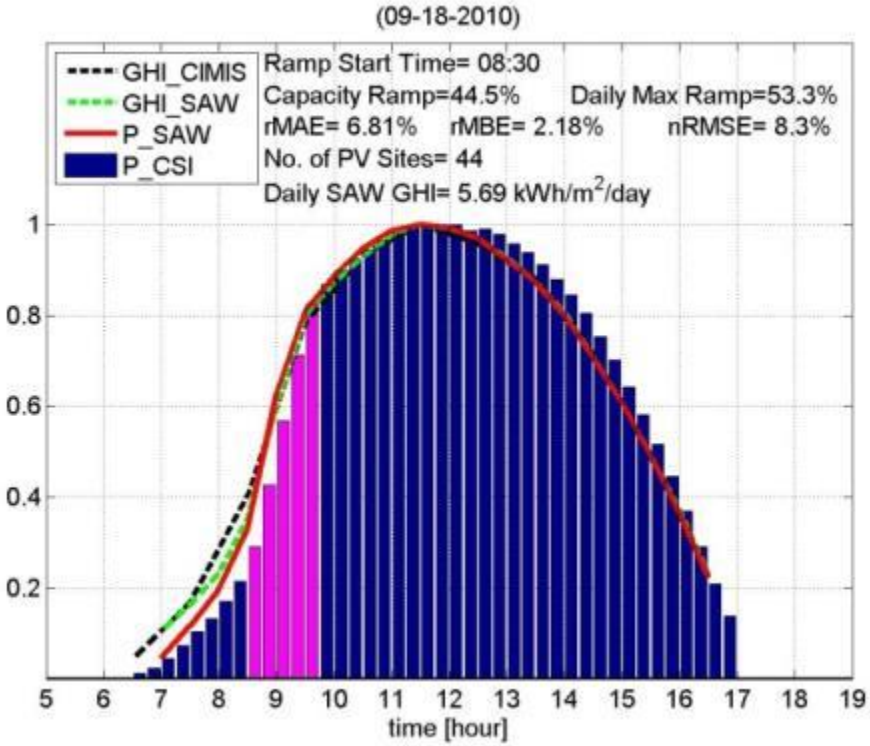
Largest step size of normalized aggregate PV output versus time interval



Cumulative distribution of absolute value of 1-hour ramp rates of normalized aggregate PV output

Two Days with the Largest Ramp Rates





Aggregate modeled & measured power of all 45 PV sites and Aggregate GHI of 5 CIMIS stations for the day with the largest 1-hour ramp rate in 2010

- Largest aggregated hourly ramp: 60.4% of PV PTC capacity
- 2nd largest ramp: 44.5%.
  - Marine layer cloud "burn-off", like many other large ramps.

Largest 2010 Ramps for all California IOUs

	SDG&E	SCE	PG&E	CAISO
Average distance between sites	28 km	101 km	186 km	332 km
Largest absolute hourly ramp	60.4%	30.7%	29.9%	29.9%
Largest weather induced ramp	55.5%	29.8%	27.6%	20.3%

- Largest ramps in SCE, PG&E, CAISO driven by changing sun angle in early morning and late afternoon during clear skies.
  - Highly predictable.
  - Anti-correlated to evening load peak.
- Relative Ramp rates do not decrease for areas beyond 60 miles.
- Weather-induced ramp rates decrease with area (56% for SDG&E versus 20% for CAISO).

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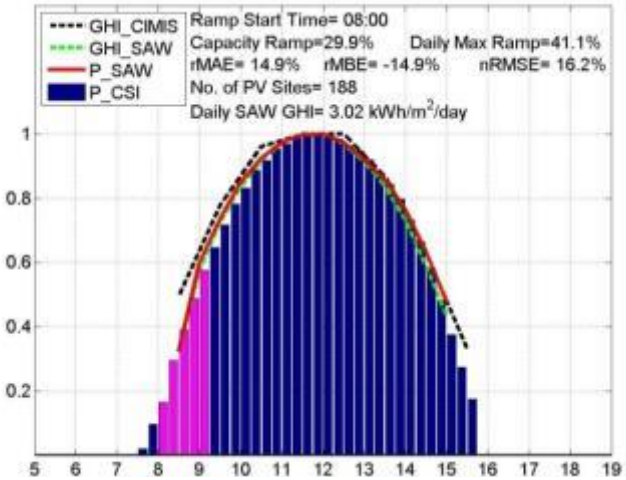
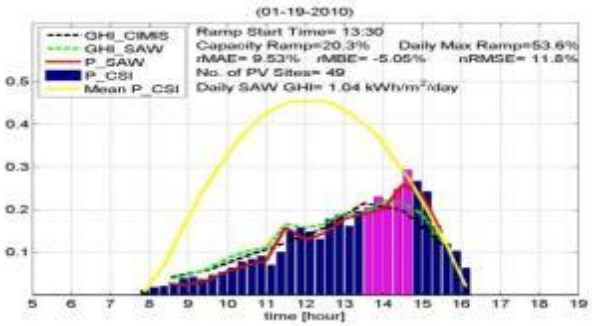
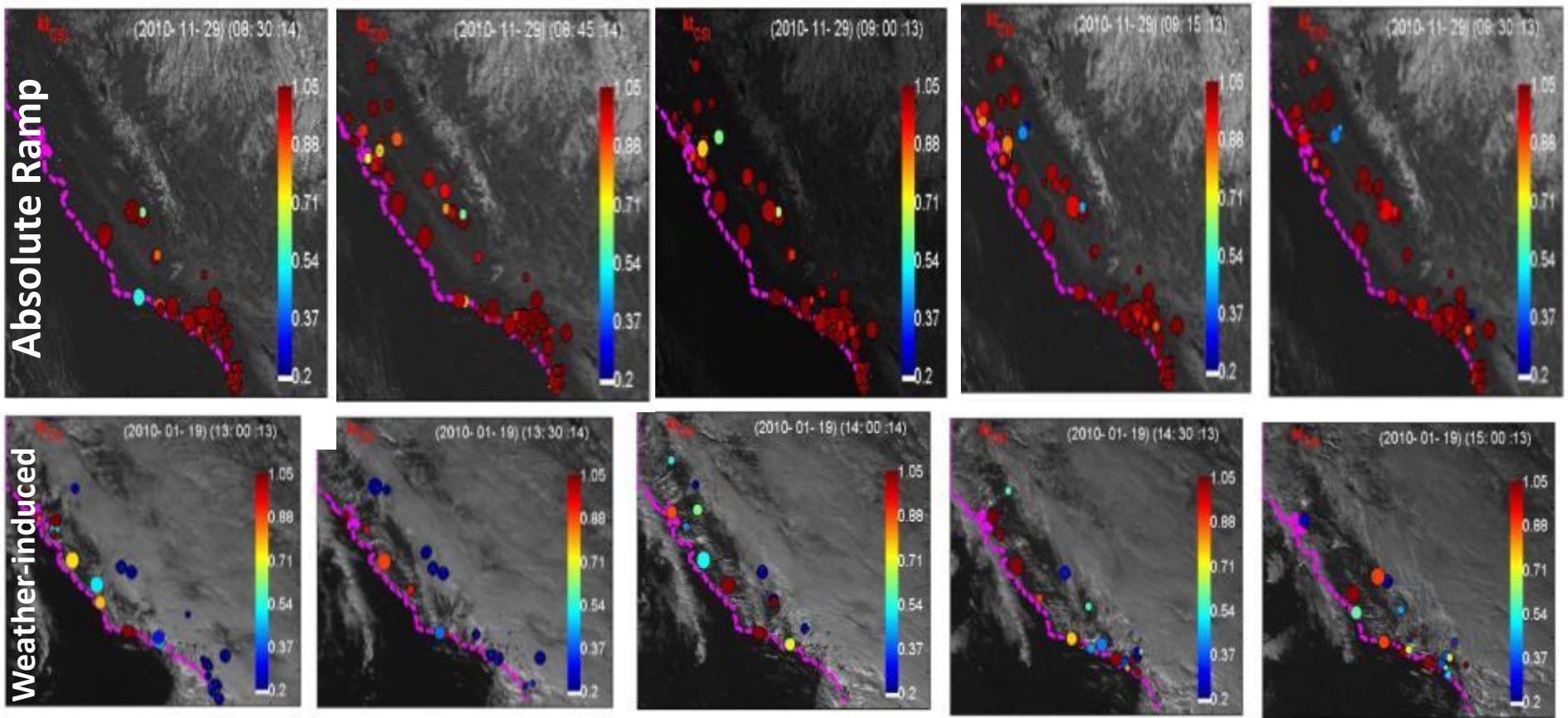
Largest Ramps in CAISO

Absolute Ramp



Weather-induced





Conclusions – Ramp Rates

- SAW modeled performance followed CSI power output in real time and matched the timing of the ramps accurately.
- For SDG&E, largest ramp 60% per hour (PTC capacity)
  - 2nd largest ramp 44% per hour
- In May through October predominantly morning up-ramps
  - Less severe, because coincident with load
- For larger territories, ramps driven by clear sky morning up and evening down ramps.
  - Weather conditions less important – 20% ramp for CAISO

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Overall Summary

- Constructed useful modeling tools for high PV penetration. Publicly available:
  - Datasets (1 sec power and 1 sec, 10 m irradiance data, horizon database)
  - Models (PV performance, variability, forecast)
- Validated SolarAnywhere
- Analyzed ramp rates for IOUs, CAISO
- Output:
  - 8 reports, 3 journal papers, 1 patent.
  - Presentations at ASES, IEEE PES, ASME conferences.
  - Commercialization with 2 partners.
  - Multiple data requests.

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